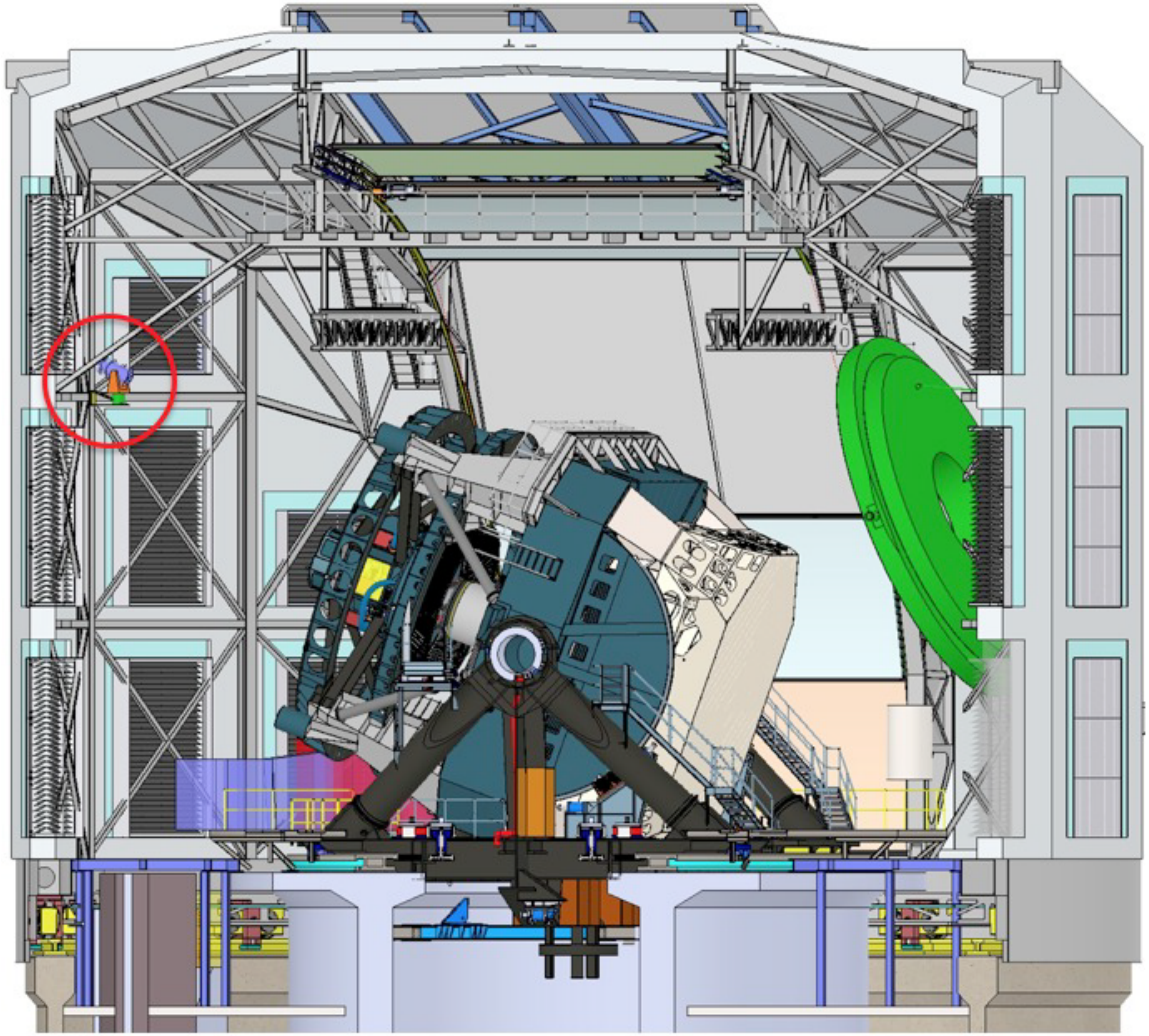
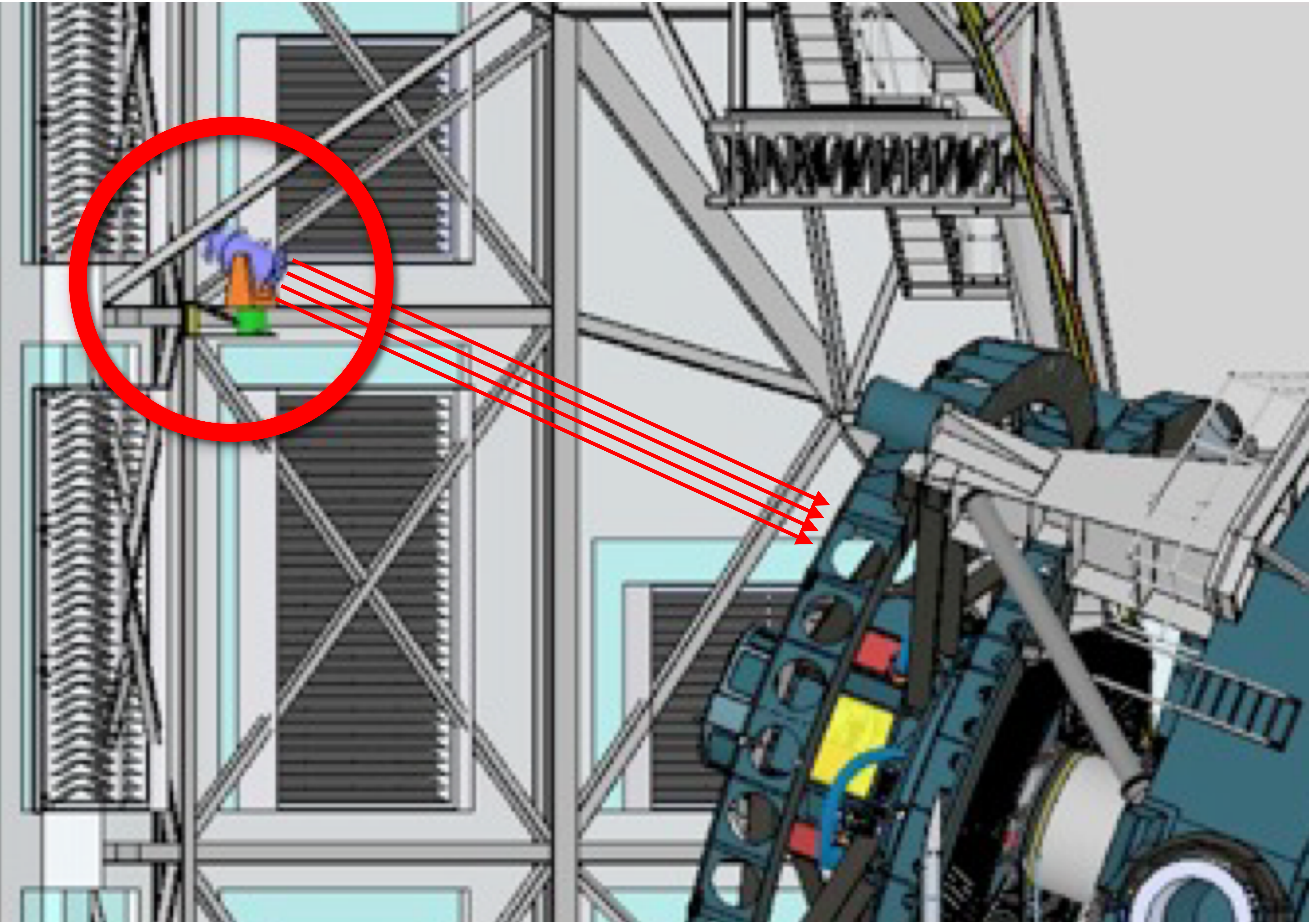
# Flattening your flats or: How I learned to stop worrying and love the CBP



Merlin Fisher-Levine - Princeton



# Why do we flat-field / what does it do?

- Corrects for amplifier-to-amplifier gain variation & pixel-to-pixel QE
  - i.e. deals the conversion between ADU and *incident* photons
- Quick history of flat-fielding:
  - Twilight flats → Wide field camera → large gradients. And what about the spectrum? Time variable night-to-night
  - Nighttime sky flats → Time variable night-to-night. Night sky spectrum
  - Conventional dome flats → Alt/az telescope + stray/scattered/ghosted light → flat-fields depend on rotator position, >5% difference. Typically incorrect input spectrum, + lamp variability
- What comes next?

# Why do we flat-field / wha[t] does it do?

- Corrects for amplifier-to-amplifier gain ... QE
  - i.e. deals the conversion be... photons
- Quick history of flat-f...
  - Twilight fl...
  - N...
  - ...ome flats →
- W...es next?

...era → large gradients.
...about the spectrum?
...ariable night-to-night

Time variable night-to-night
Night sky spectrum

Alt/az telescope + stray/scattered/ghosted light
→ flat-fields depend on rotator position, >5% difference
Typically incorrect input spectrum, + lamp variability

**Flat-fields with monochromatic illumination + a CBP**

# What is a CBP

Please note that despite the ponytail
and inept use of a telescope,
that is not Robert!
(You can tell from the shoes)

- CBP stands for *Collimated Beam Projector*
- Essentially, it's a telescope "*run backwards*"
- A telescope is a device which maps ***angles*** to ***positions***

*So reversing this…*

- A CBP is a telescope which takes a mask at what would have been its focal plane, and projects light through it.

# What is a CBP


- CBP stands for *Collimated Beam Projector*
- Essentially, it's a telescope "*run backwards*"
- A telescope is a device which maps ***angles*** to ***positions***

*So reversing this…*

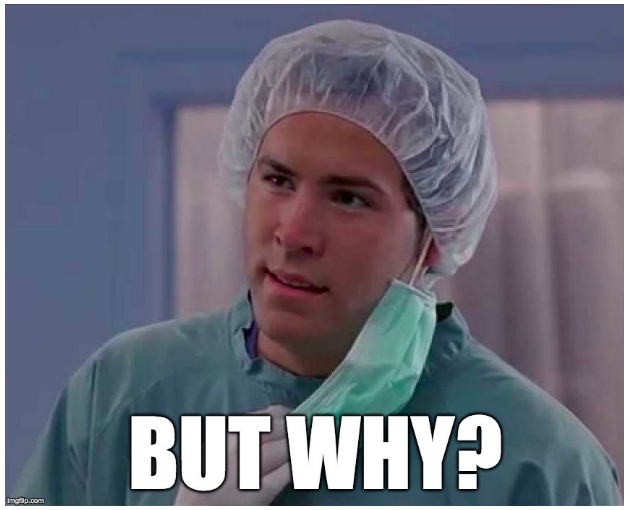
- This results in multiple "pencil-beams" of light coming out of the CBP (see Giles the cheese hedgehog)
- The angles at which these beams exit the CBP are defined by the position of the holes in the mask

# What is a CBP

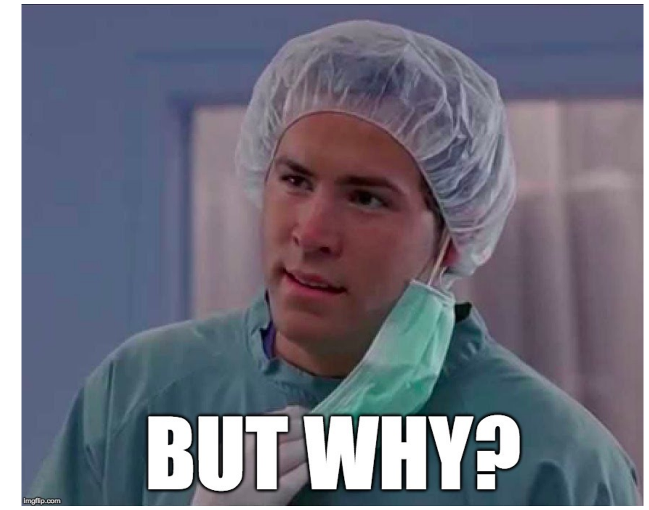
- CBP stands for *Collimated Beam Projector*
- Essentially, it's a telescope "*run backwards*"
- A telescope is a device which maps ***angles*** to ***positions***

*So reversing this…*

- The mask pattern is therefore re-imaged by the observing telescope onto *its* focal plane
- Meaning we can place spots of our choosing at will




# But why?

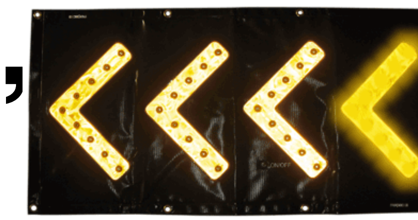



- Because it mimics a (monochromatic) source at infinity
- And because the diameter of these output beams == the diameter of the CBP telescope (~30cm)
    - it's finite (unlike the planar wavefront from stars)
    - and therefore only samples a portion of the optics of the main telescope (primary mirror, filters etc.)
- These properties mean it can be used for all sorts of fun things…

# Like what?

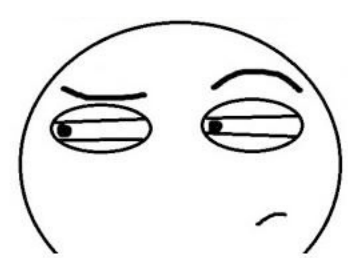
A Collimated Beam Projector allows us to:

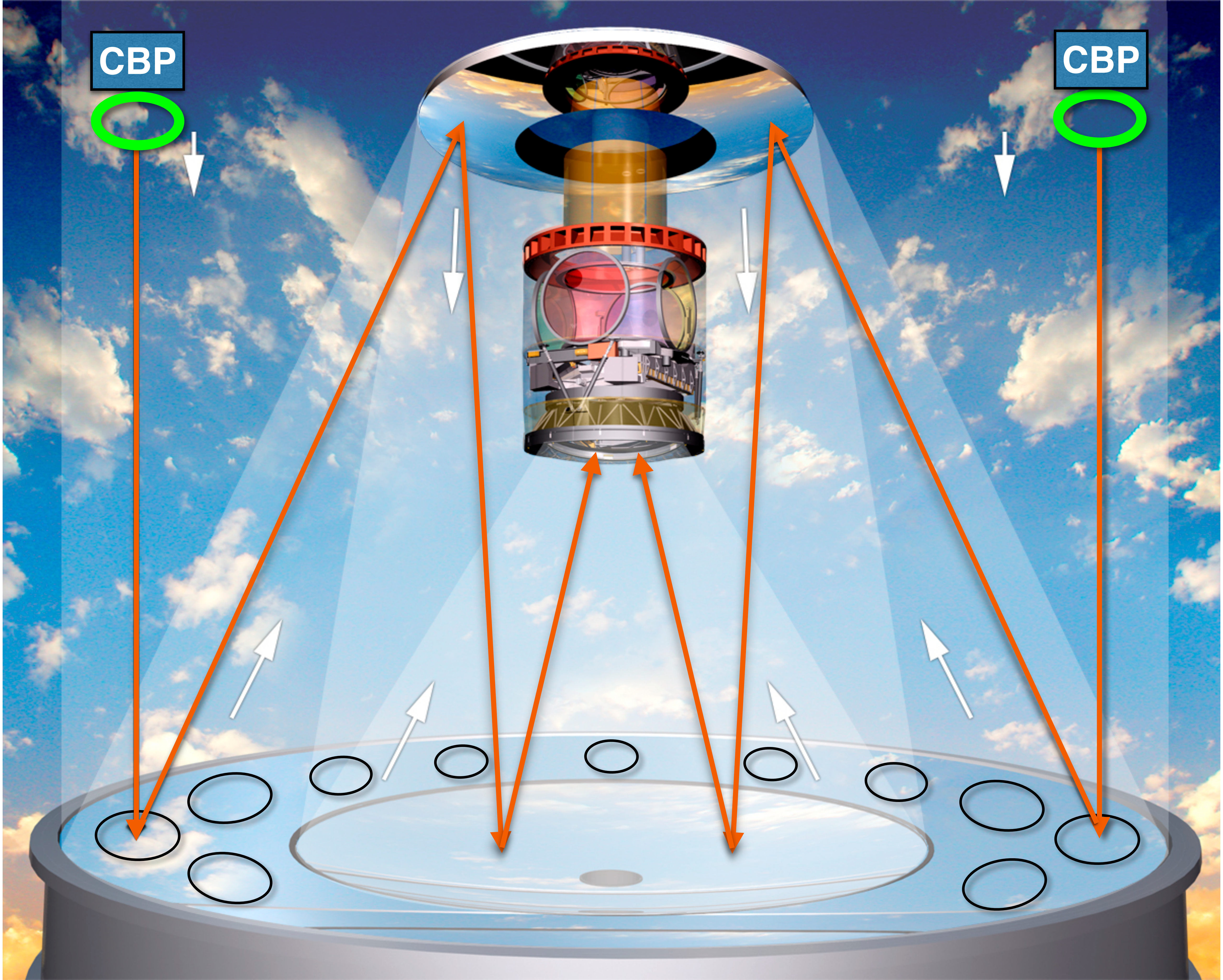
**Make ‘photometric flat-fields’**



And also, *as an aside*:

- Monitor the filter transmission profiles, including as a function of position on the filter
    - Although we are assured that the LSST filter edges won’t move over time (unlike every filter ever made previously), it is probably prudent to confirm/measure this.
- Provides a convenient alternative method to differentiate between between electronic crosstalk and optical ghosting, i.e. without relying on cosmics (low signal) or bleed trails (messy)
- Measure absolute throughput (?!?!)




CBP
CBP

# Variable definitions

System response function

$$\boxed{S_{sys} = S_{QE}\, S_{pixel}\, S_{optical}}$$

Flat-field observation

$$\boxed{F = (1 + i + A)\, S_{sys}}$$

- $S_{QE}$ = System response due to quantum efficiency ← Multiplicative
- $S_{optical}$ = System response from optical distortions ← Multiplicative

    (Different pixels subtend different areas on the sky)

- $S_{pixel}$ = (static) pixel size variations: intrinsic variation, tree-rings
- $i$ = non-uniformity in the flat-field screen illumination ← Additive
- $A$ = ghosting/scattered light from the flat-field screen ← Additive
- Other effects:
    - Vignetting - flat in $\lambda$, but degenerate with QE, opposite in sign to $S_{optical}$

# Flat-field Illumination (*i*)

$i = 0.05x^2$

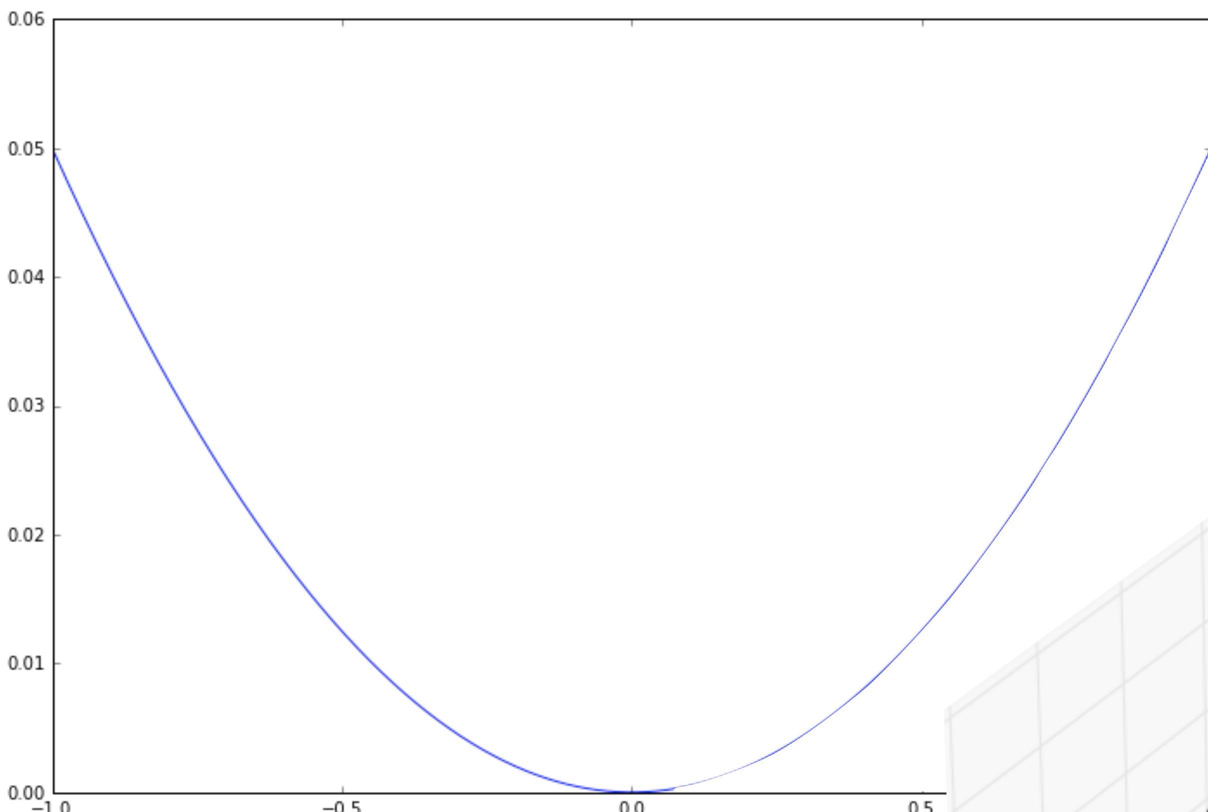
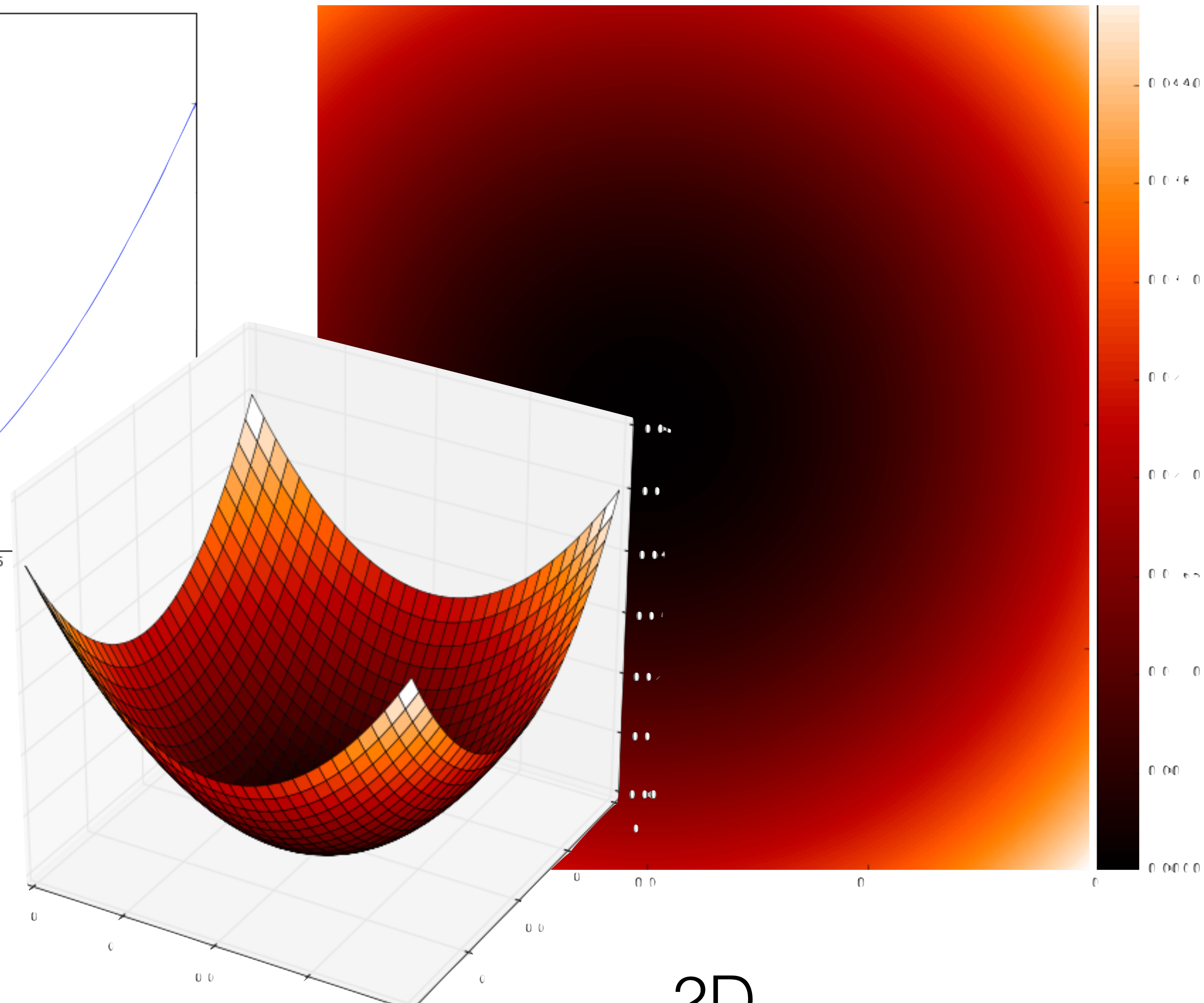



Figure credit: R. Lupton

$i = 0.05x^2 + 0.05y^2$



1D

2D

# Ghosting ($A$)

$A = -0.07 \cos(2\pi x)$

$A = -(0.04 \cos(\pi x) + 0.04 \cos(\pi y))$

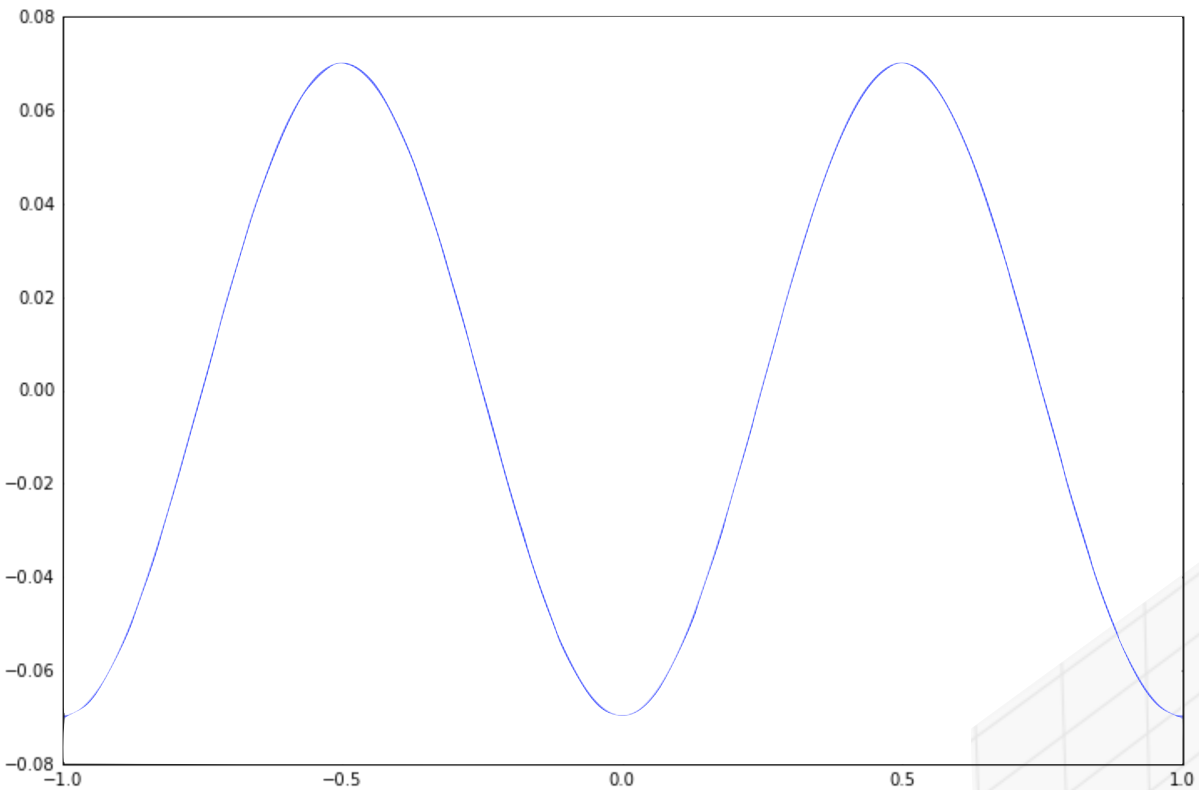
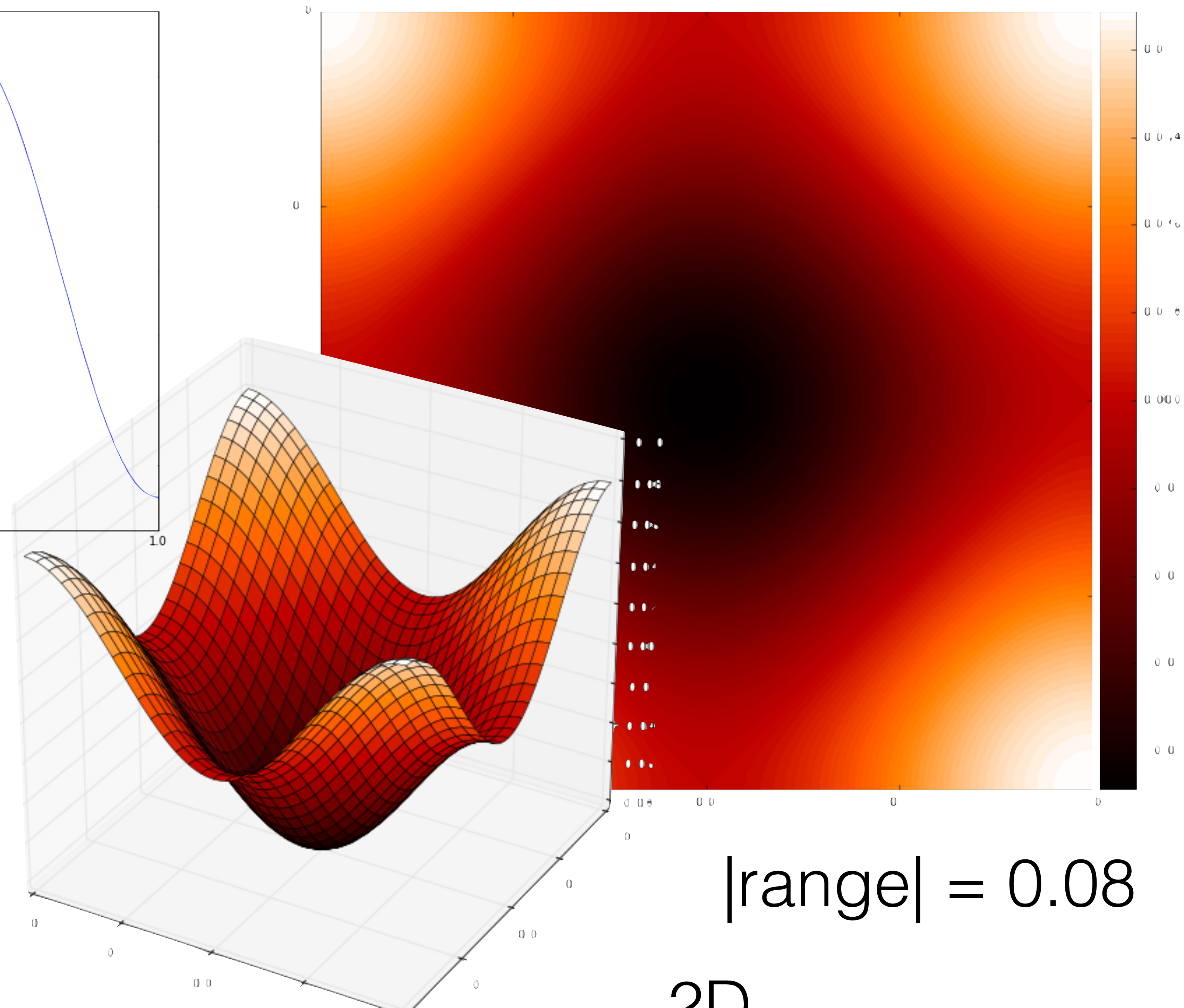



Figure credit: R. Lupton



|range| = 0.08

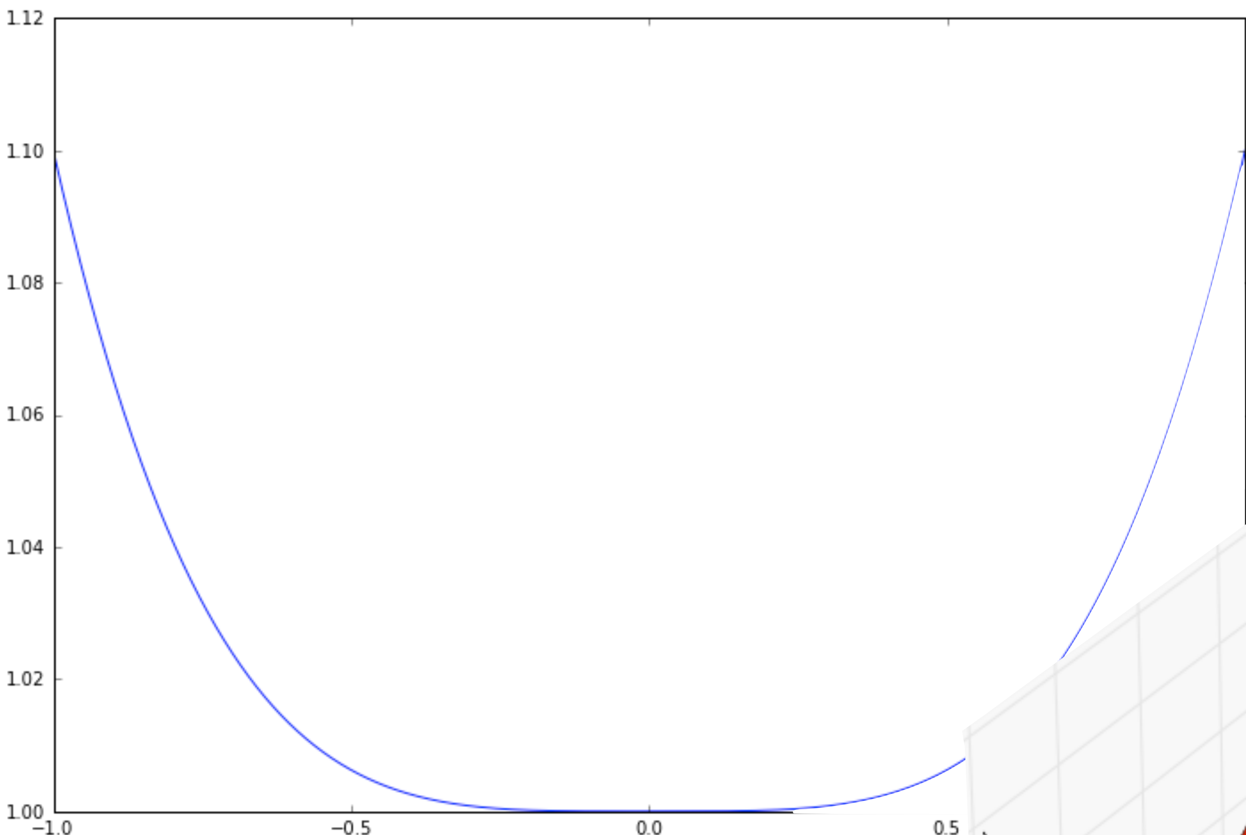
1D

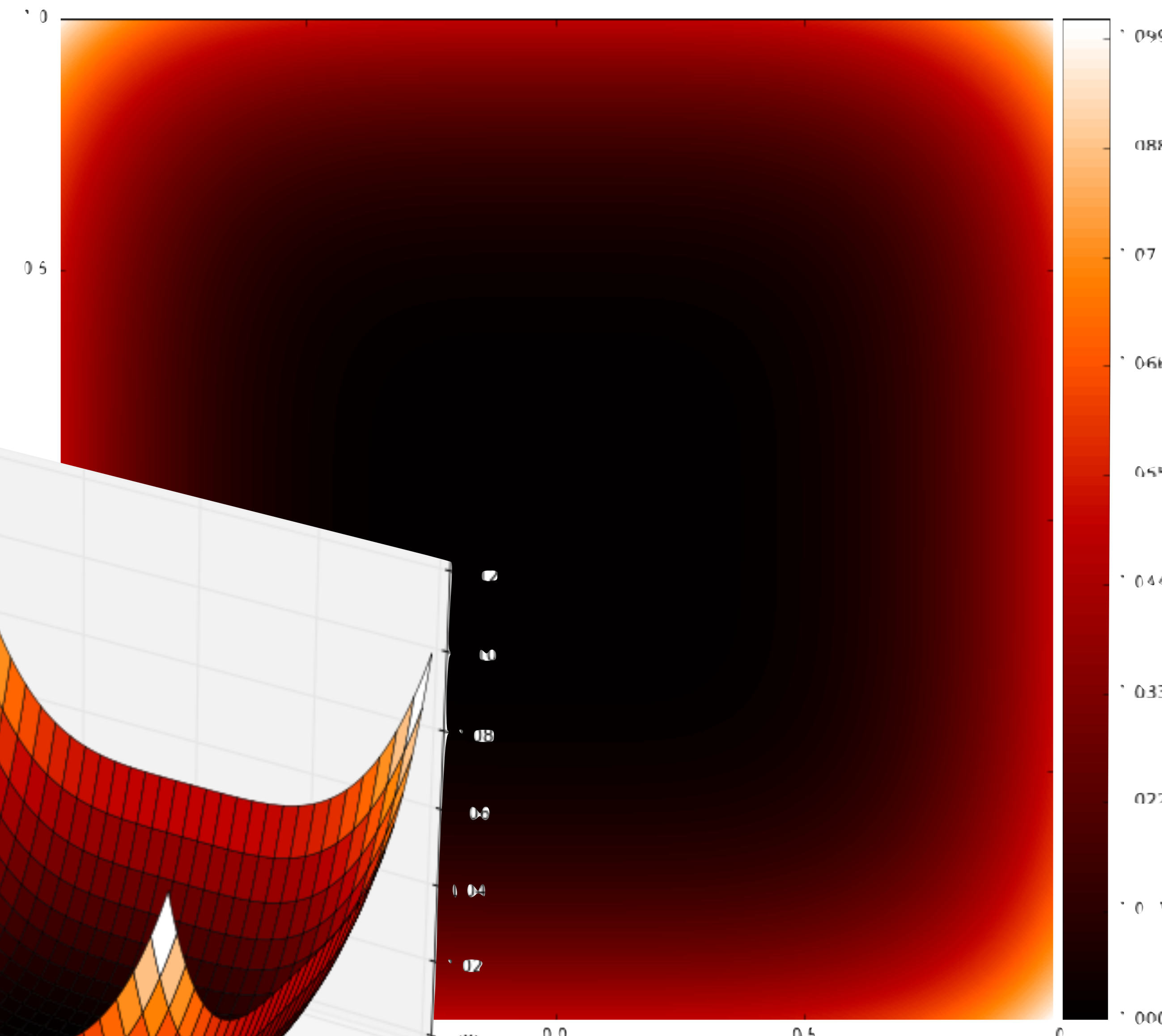
2D

# Optical Distortion ($S_{optical}$)

$S_{optical} = 1 + 0.1x^4$

$S_{optical} = 1 + 0.1x^4 + 0.1y^4$



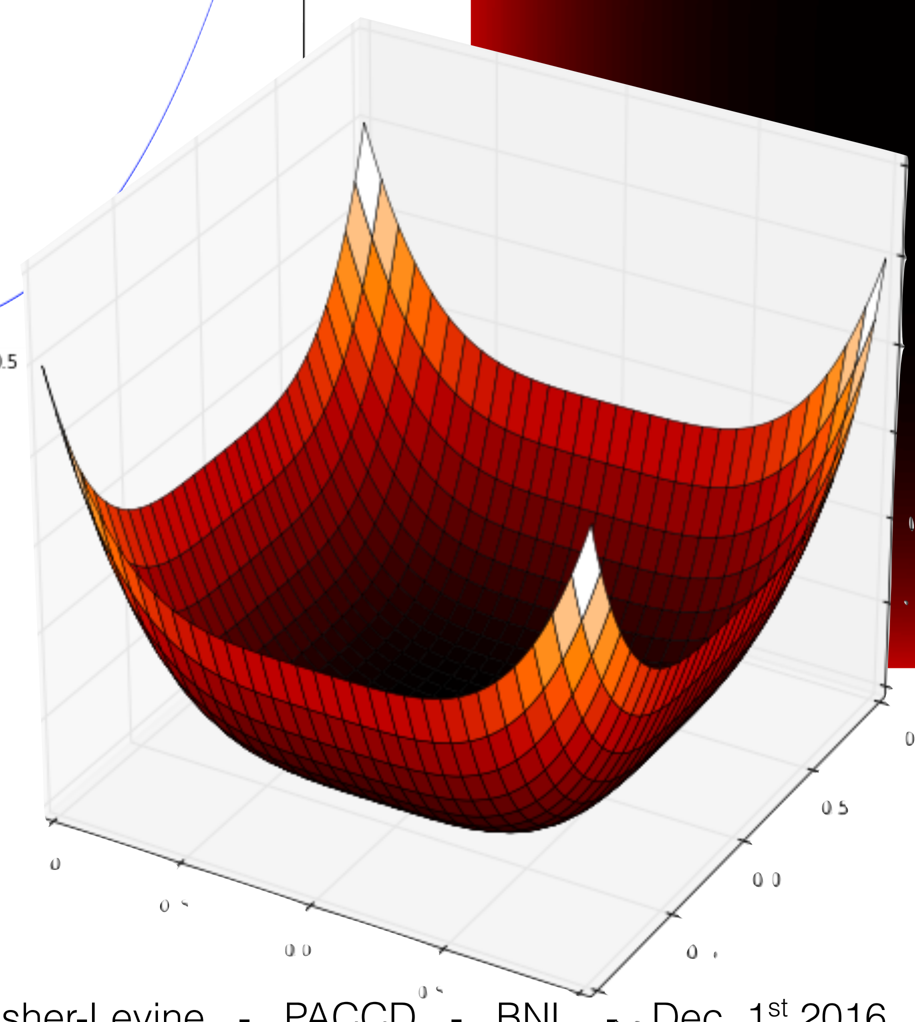


Figure credit: R. Lupton

1D

2D

# Quantum Efficiency ($S_{QE}$)

$S_{QE}$ = *piecewise linear*

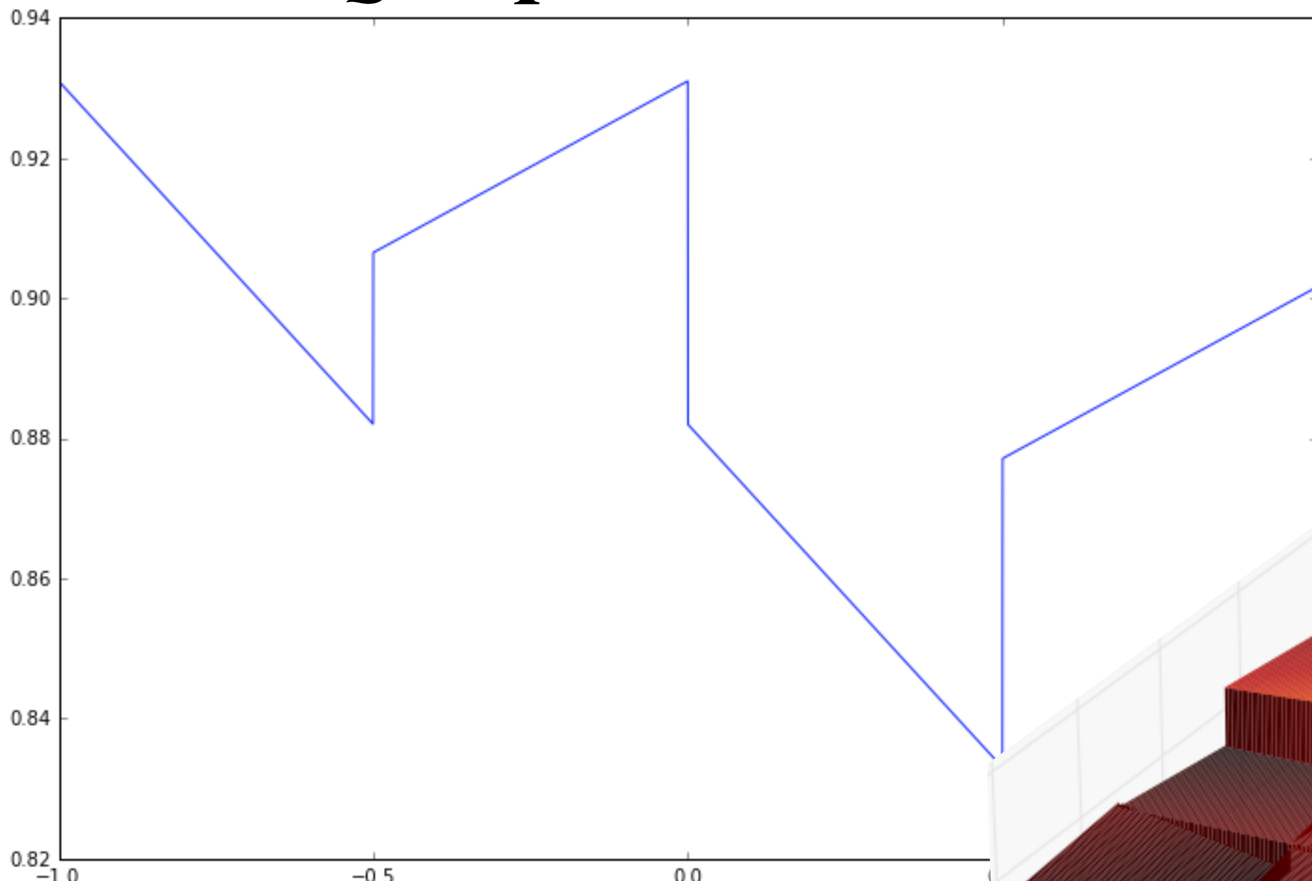
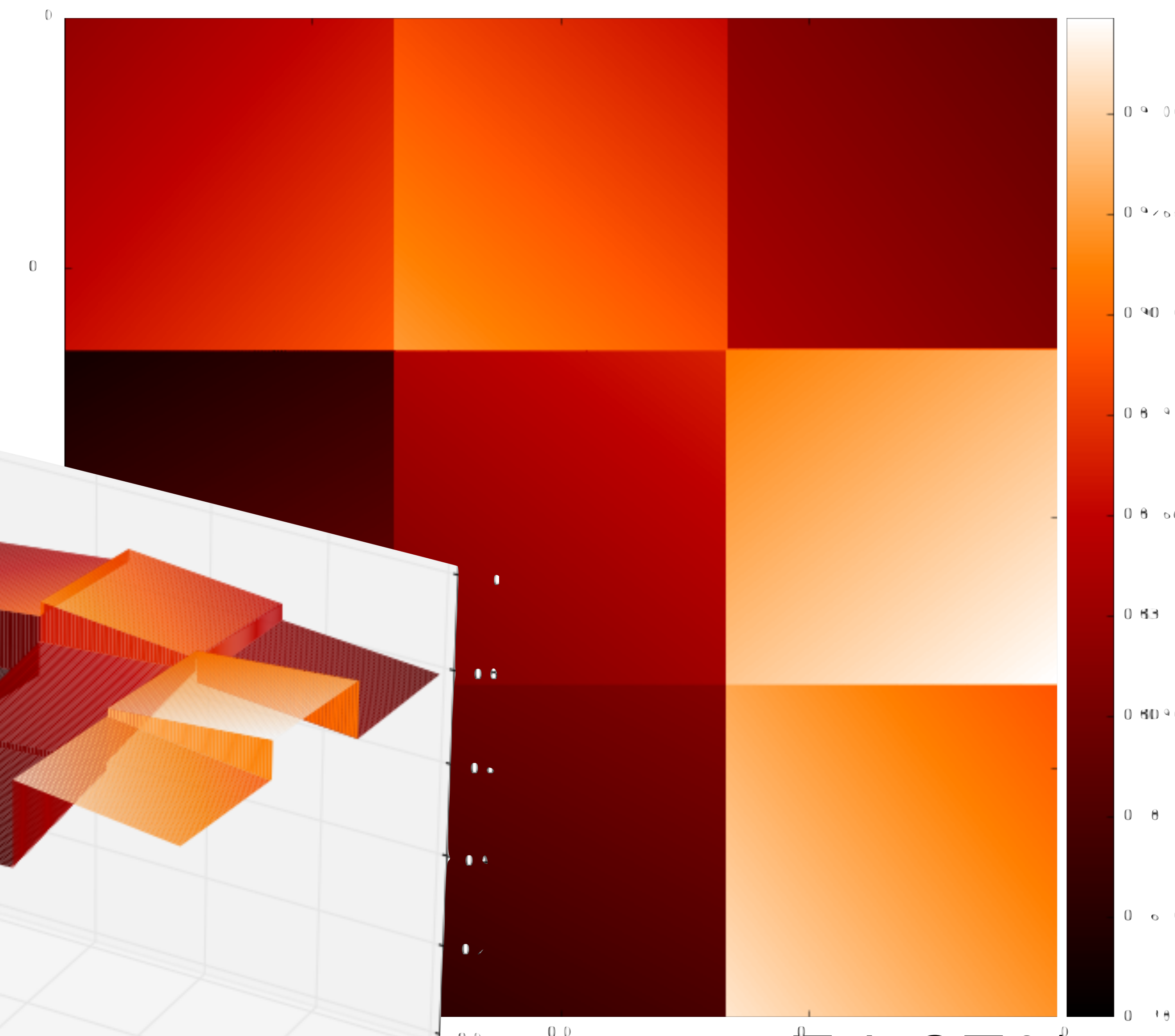
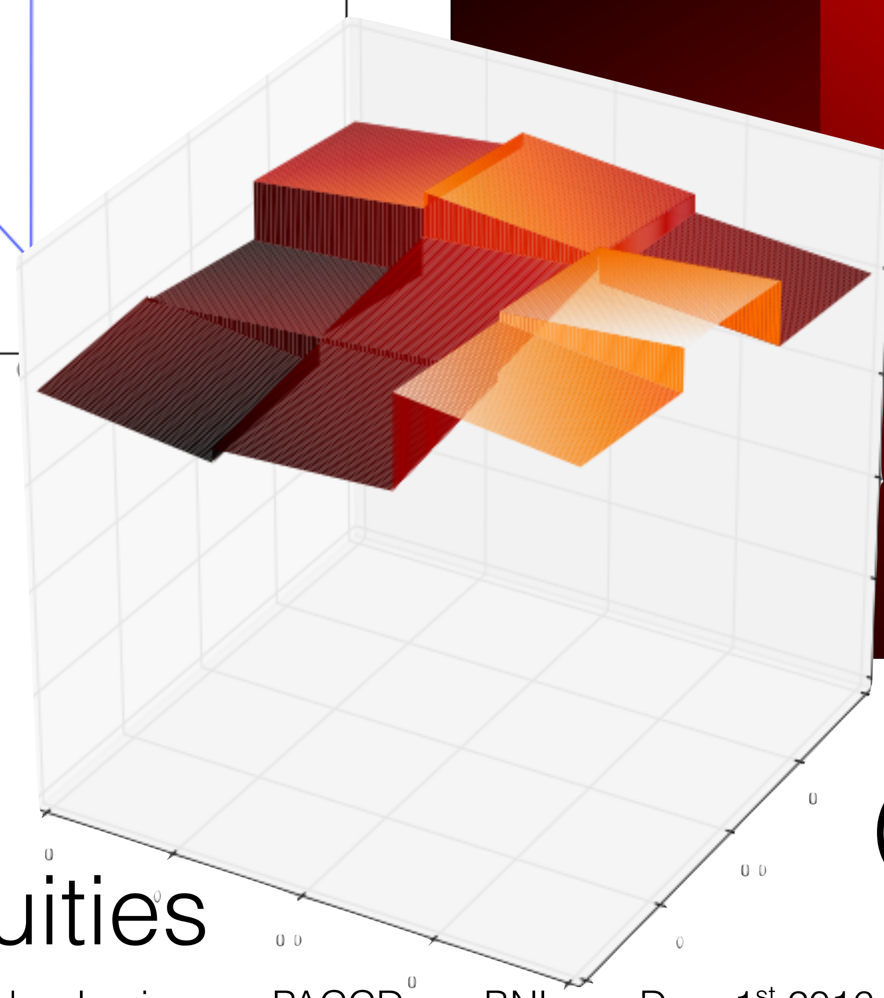



Figure credit: R. Lupton

$S_{QE}$ = *piecewise bi-linear*





- Random gradients in $x$ and $y$
- Random nominal QE
- Introduces discontinuities

range = 74-97%
(no chromaticity)

2D

# Pixel Sizes ($S_{pixel}$)

$$S_{pixel} = 1 + 0.01 \sin(50\pi x)$$

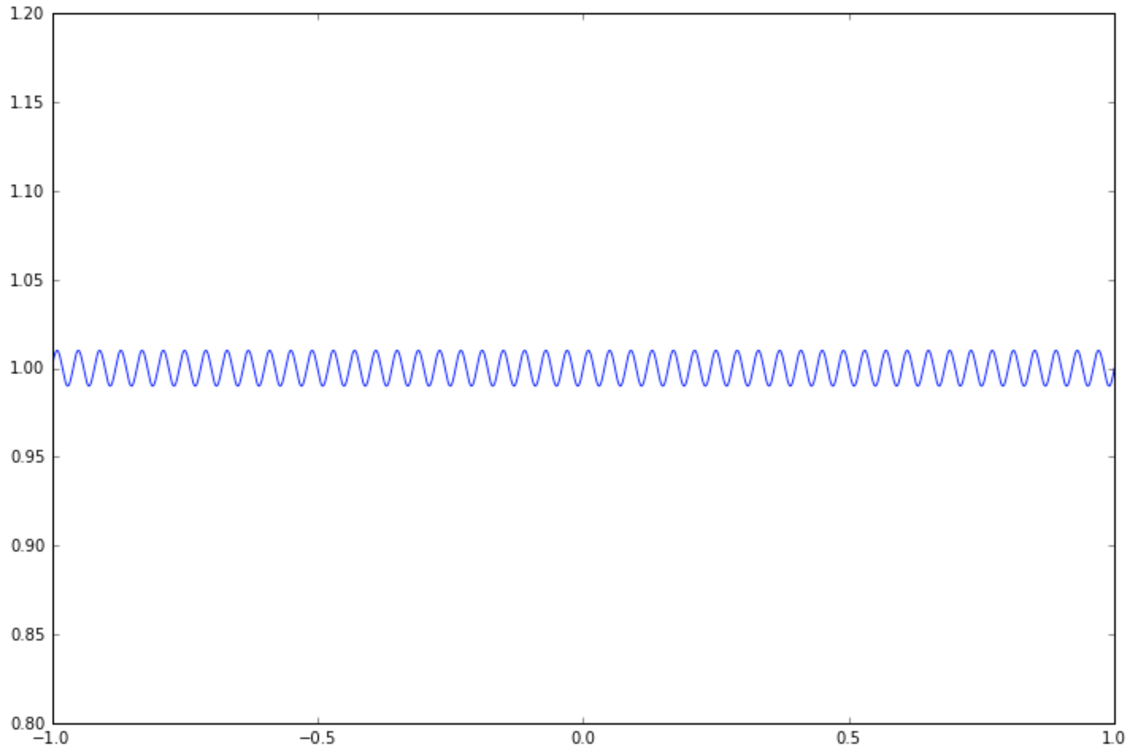


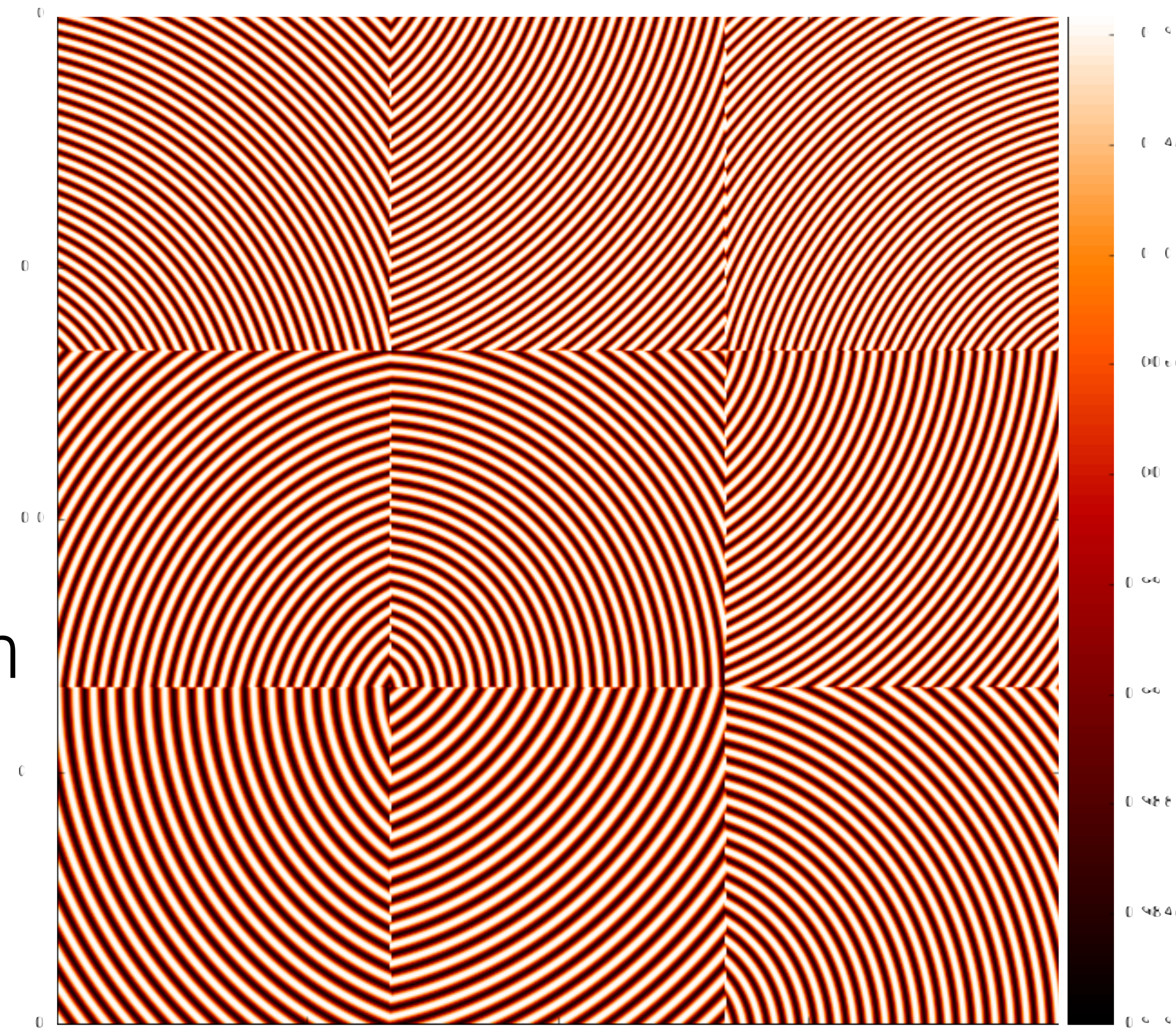

Figure credit: R. Lupton

- Origins off-chip by random amount → random phase
- Incommensurate periods
- Random chip orientation

1D

$$S_{pixel} = 1 + 0.01 \sin(\nu_i \pi x + \phi_i)$$

$$\nu = [59, 61, 67, 71, 73, 79, 83, 89, 97]$$



2D

# Pixel Sizes ($S_{pixel}$)

$$S_{pixel} = 1 + 0.01 \sin(50\pi x)$$

$$S_{pixel} = 1 + 0.01 \sin(v_i \pi x + \phi_i)$$

$$v = [59, 61, 67, 71, 73, 79, 83, 89, 97]$$

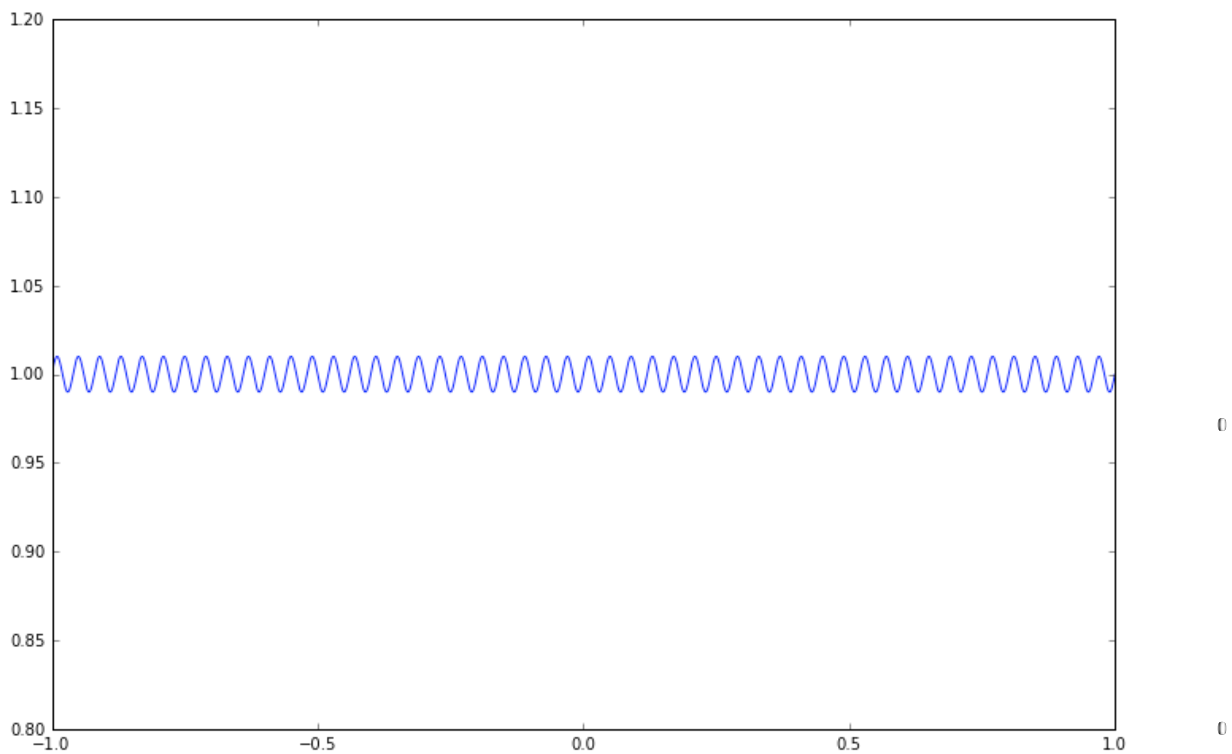
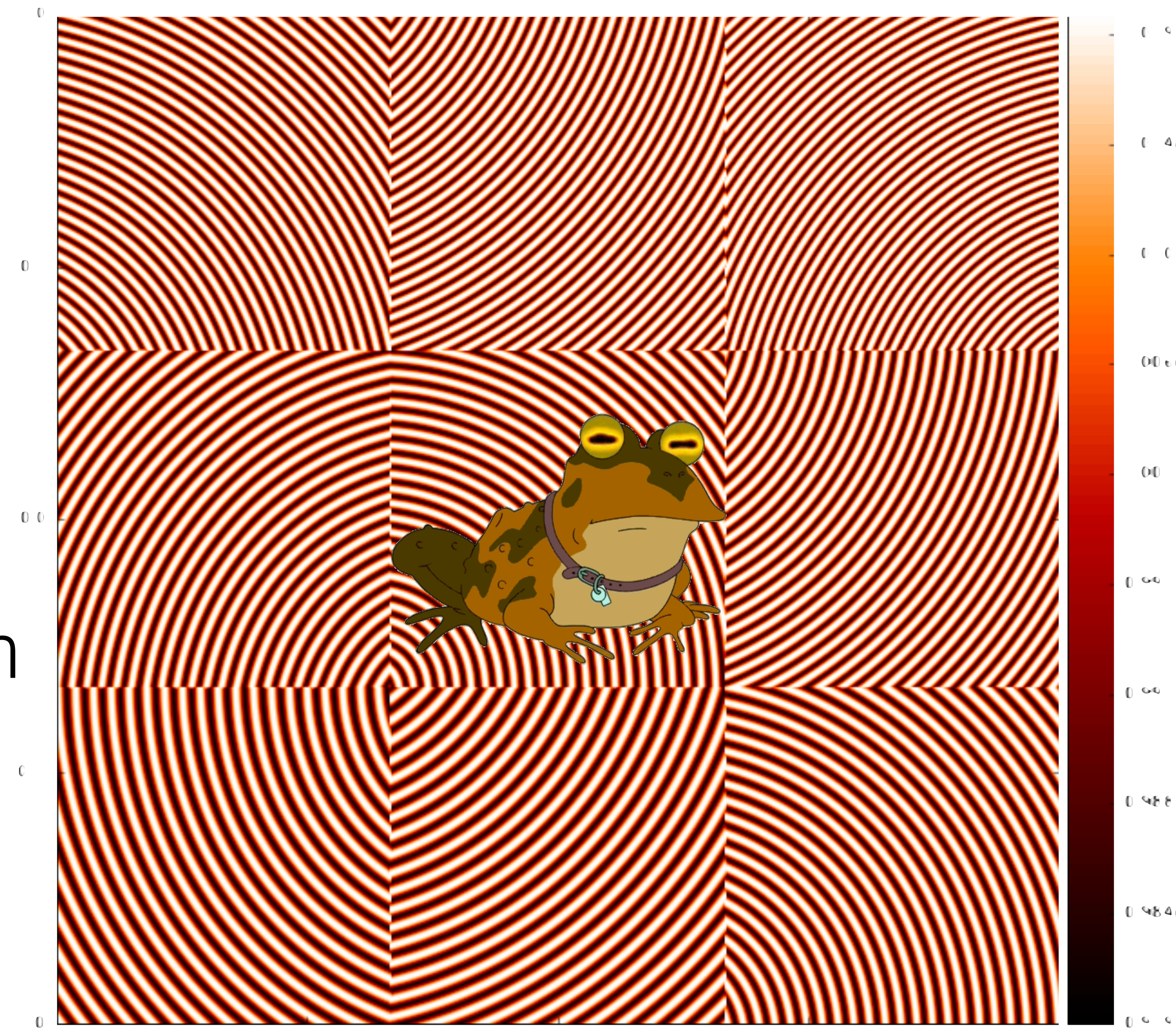



Figure credit: R. Lupton



- Origins off-chip by random amount → random phase
- Incommensurate periods
- Random chip orientation

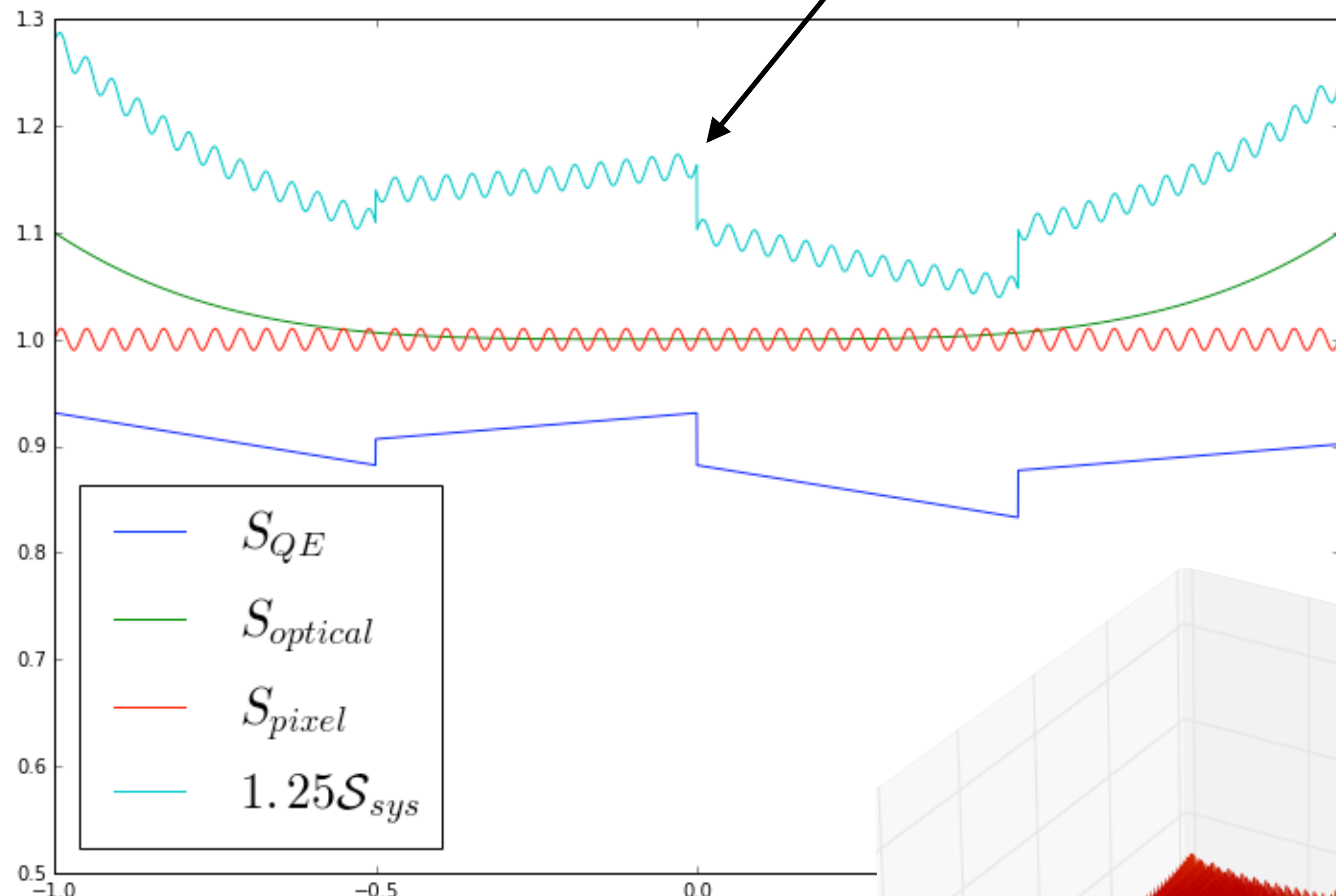
1D

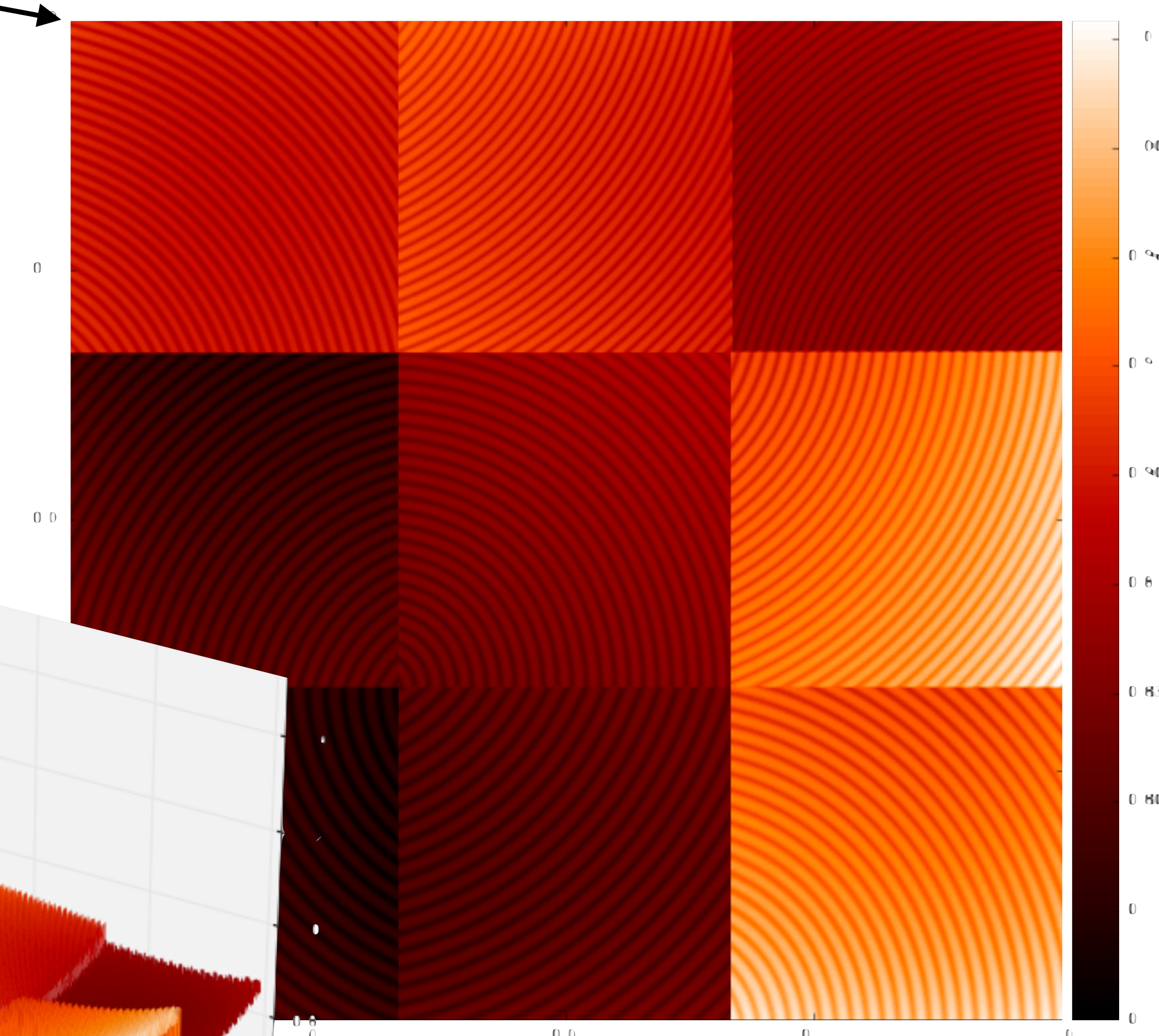
2D

# Putting these together…

System response function

$$\boxed{S_{sys} = S_{QE}\, S_{pixel}\, S_{optical}}$$



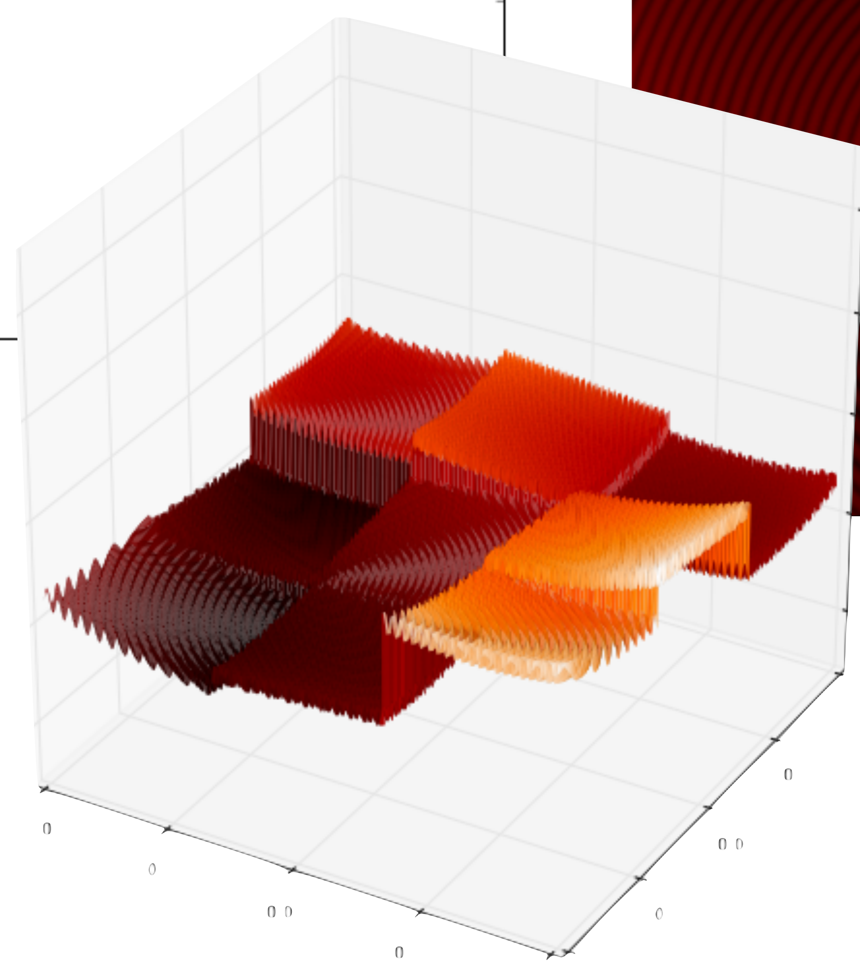


Figure credit: R. Lupton

1D

2D

Flat-field observation

$$F=(1+i+A)S_{sys}$$

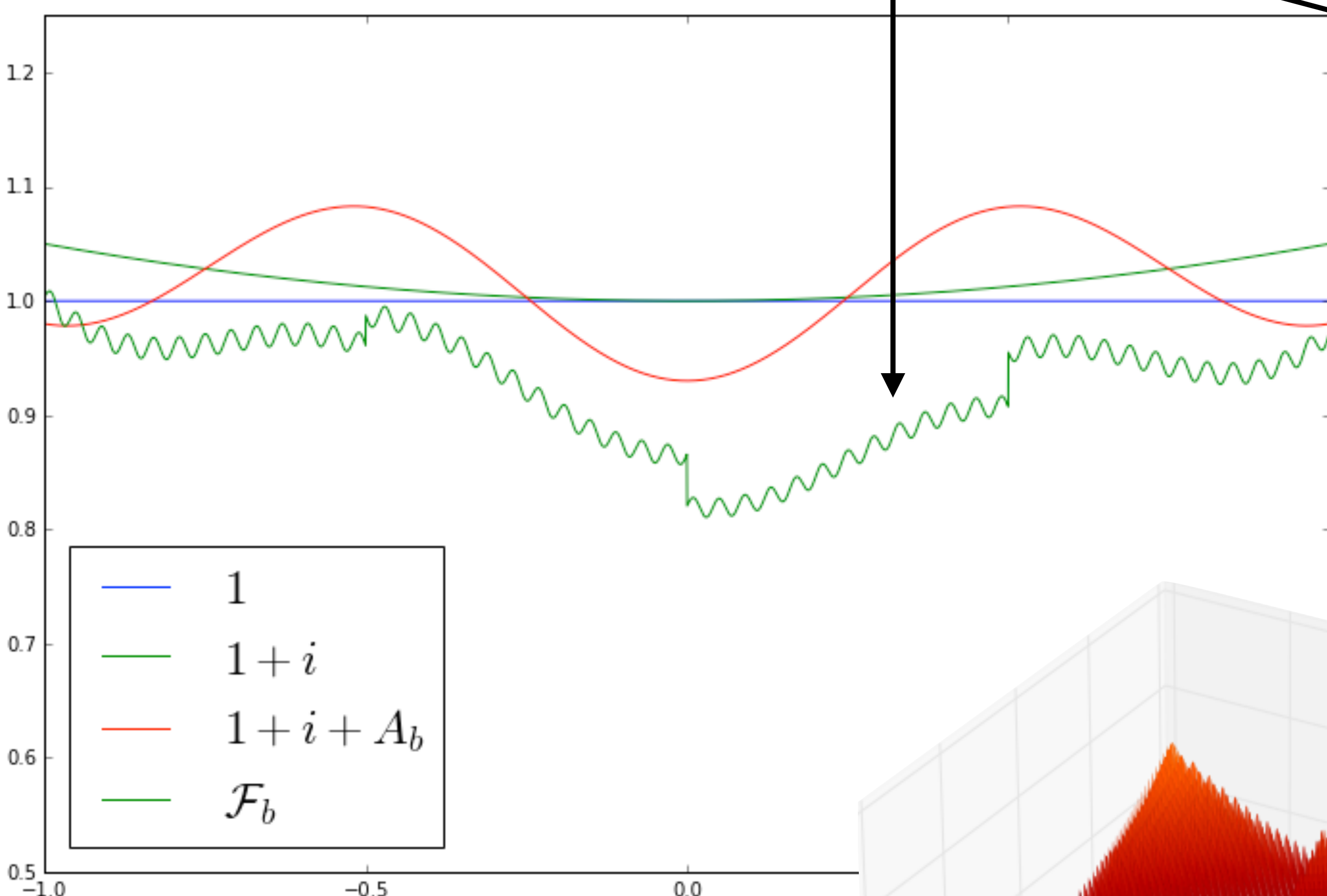
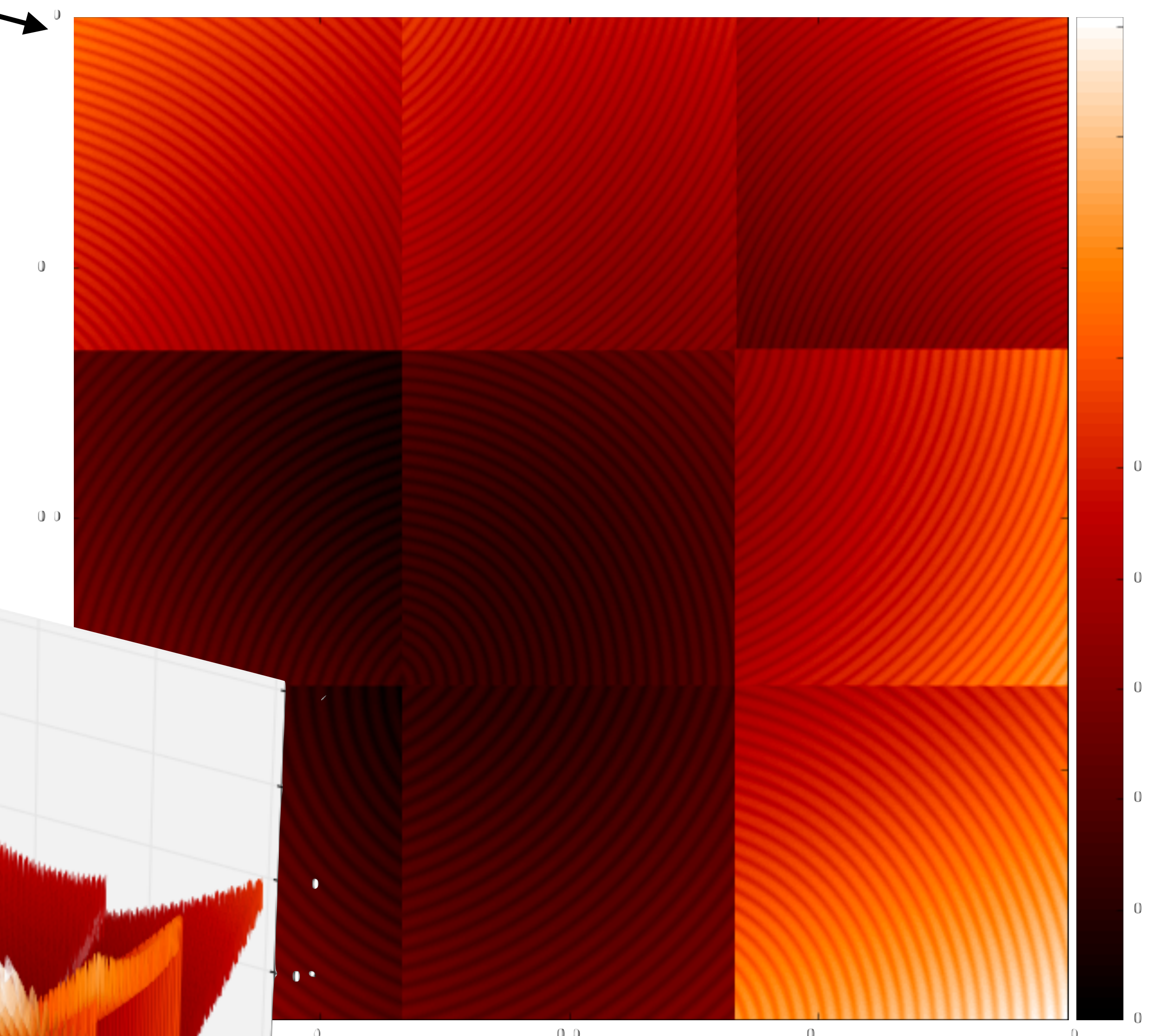
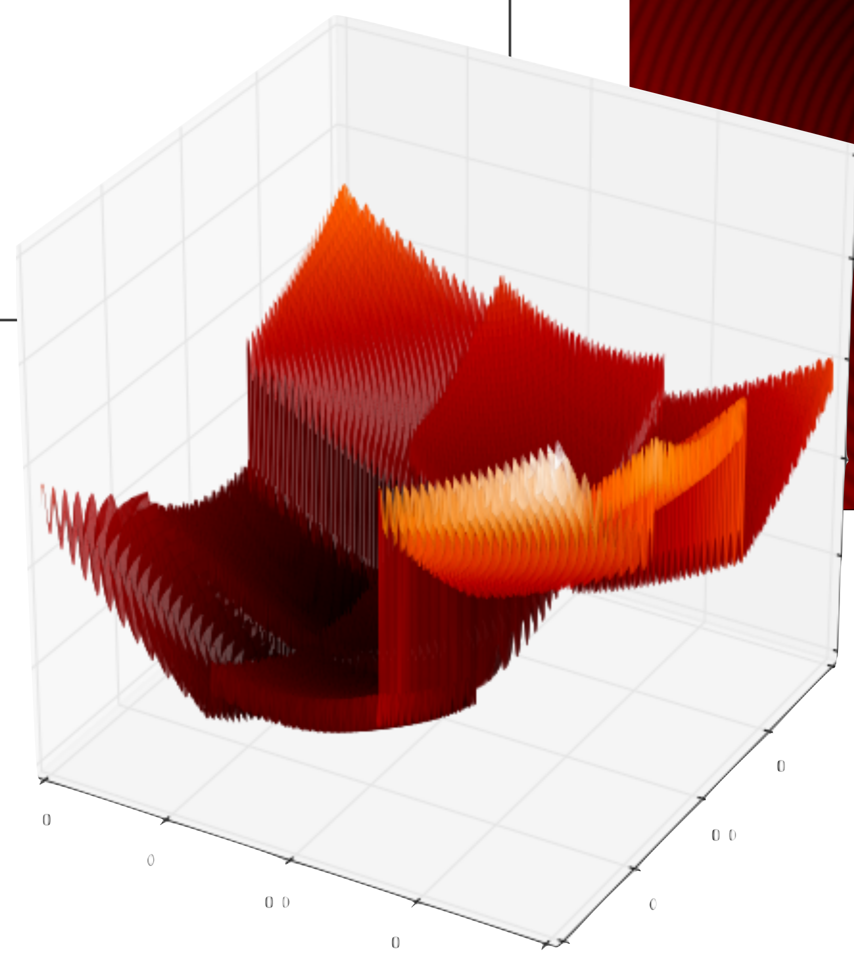



Figure credit: R. Lupton





1D

2D

# Reconstruction from CBP data (1)

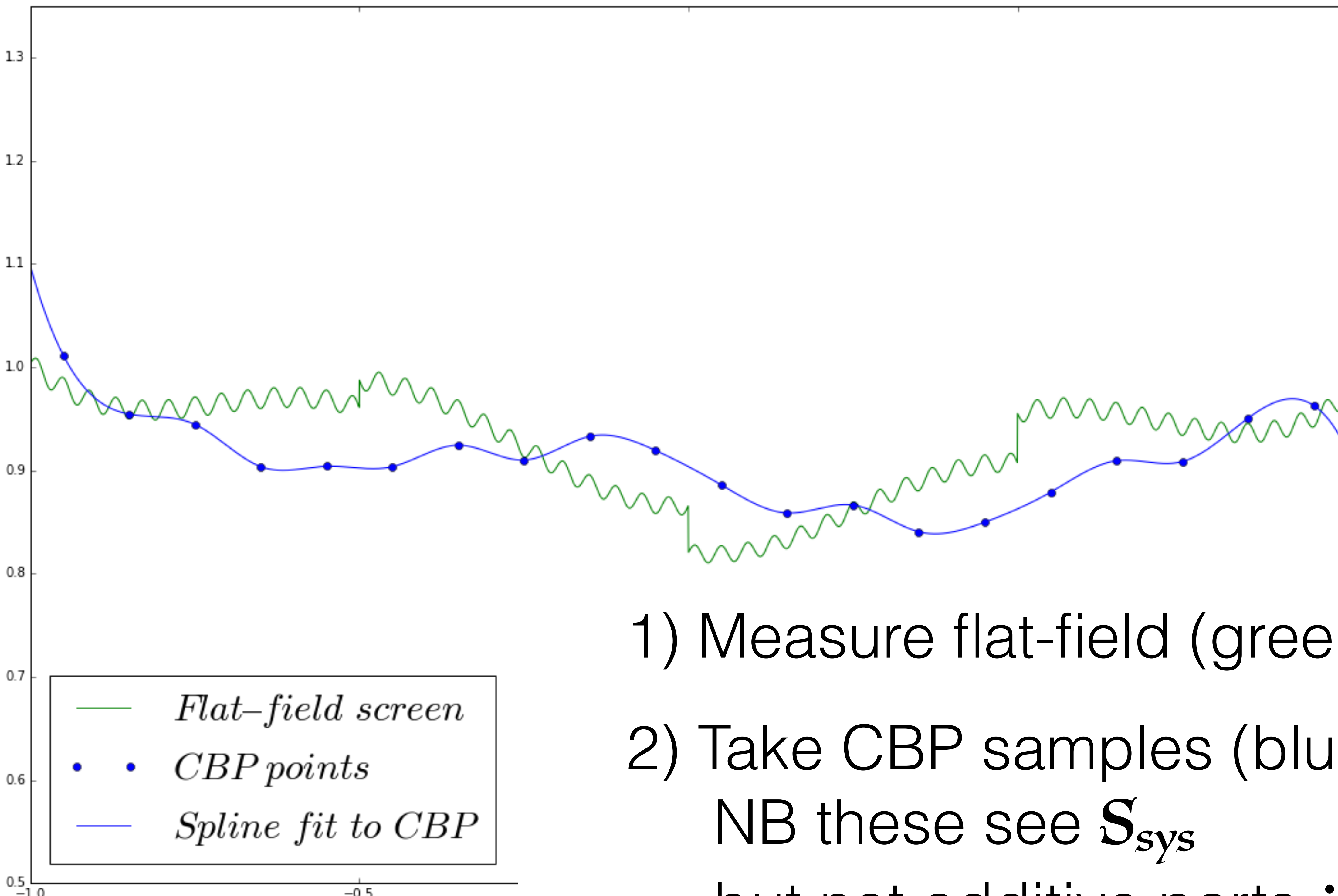



Figure credit: R. Lupton

1) Measure flat-field (green)

2) Take CBP samples (blue)
   NB these see $\mathbf{S}_{sys}$
   but not additive parts $\boldsymbol{i} + \boldsymbol{A}$

3) Spline interpolate

# Reconstruction from CBP data (1)

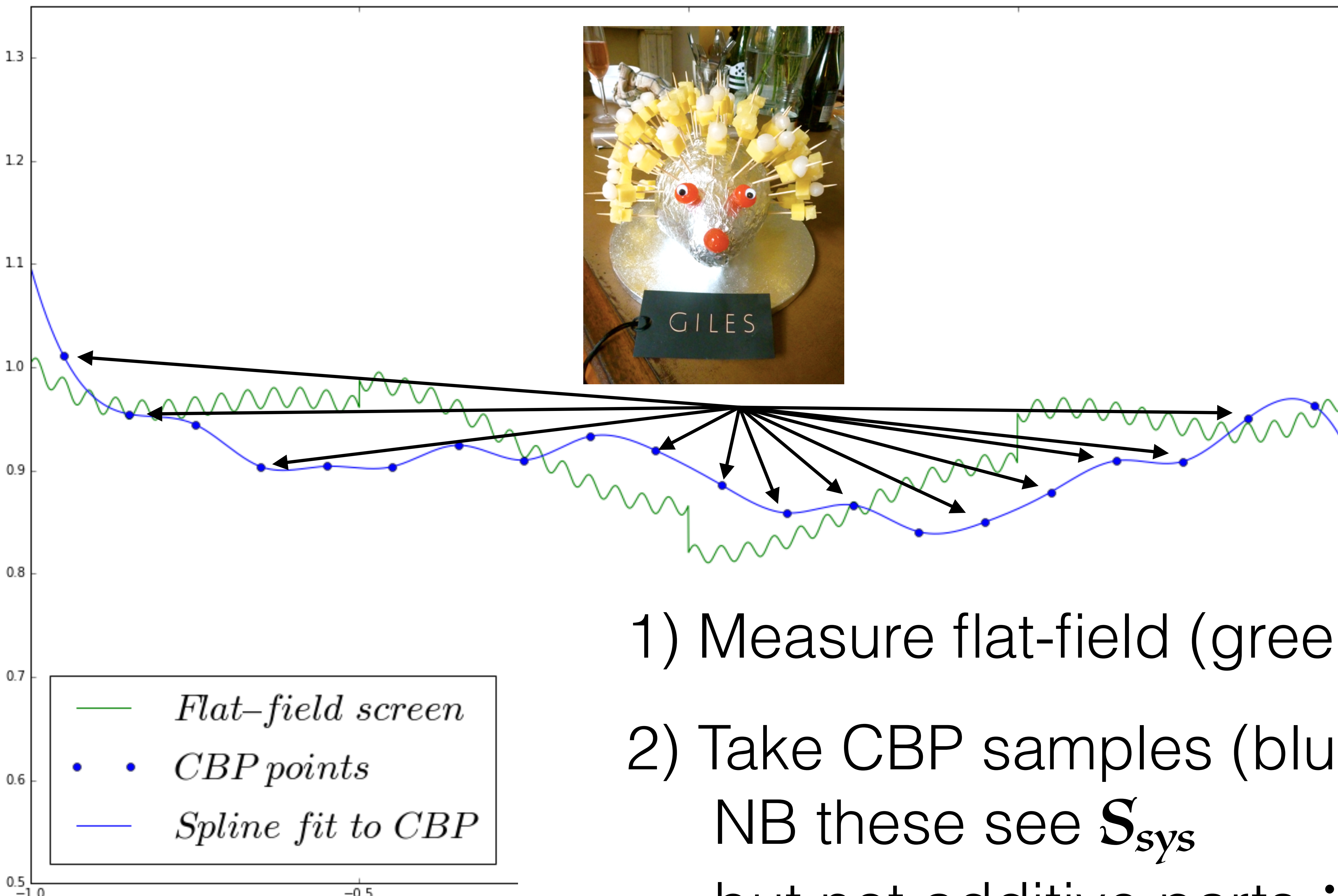



Figure credit: R. Lupton

1) Measure flat-field (green)

2) Take CBP samples (blue)
NB these see $\mathbf{S}_{sys}$
but not additive parts $\boldsymbol{i} + \boldsymbol{A}$

3) Spline interpolate

# Reconstruction from CBP data (2)

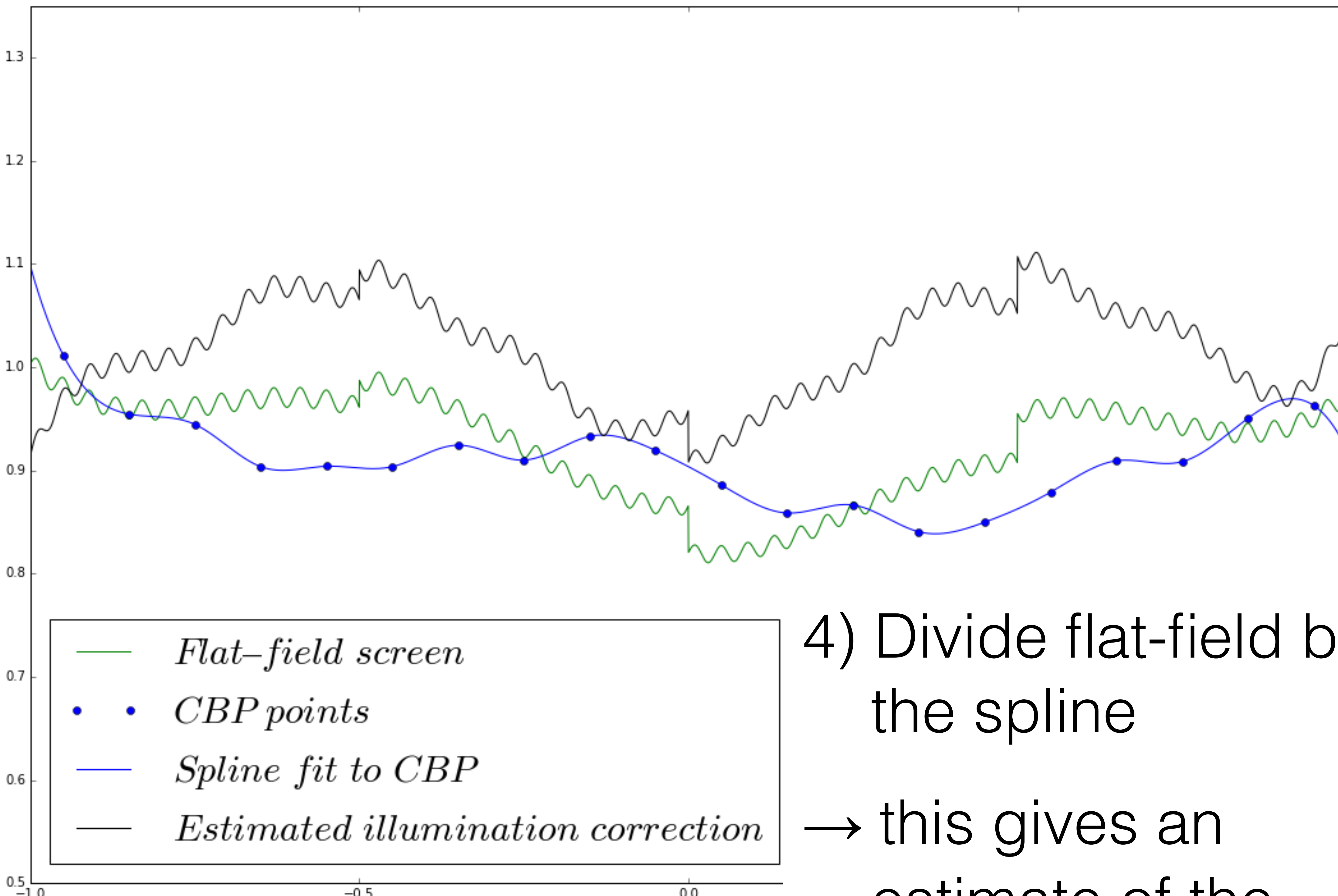
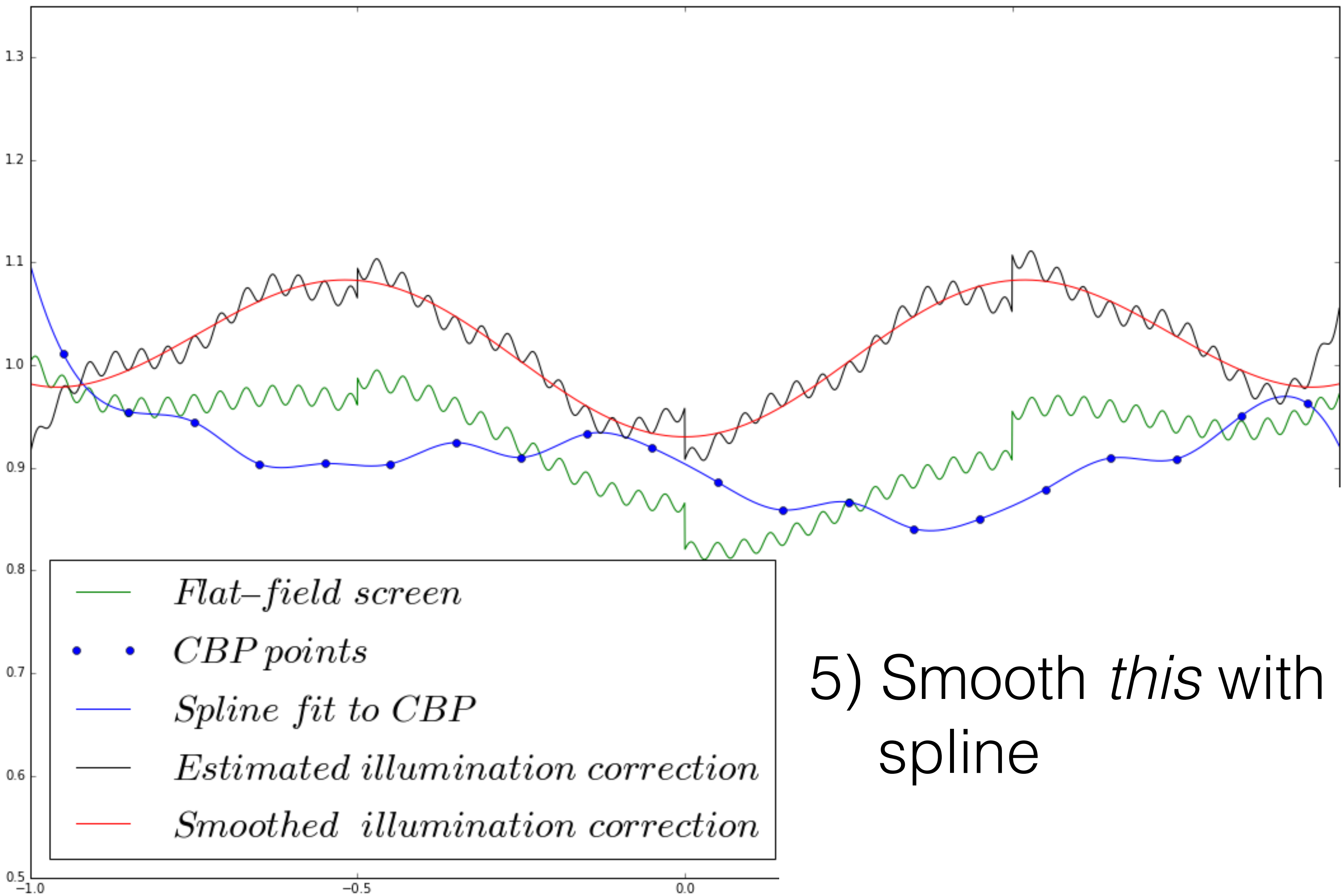



Figure credit: R. Lupton

4) Divide flat-field by the spline

→ this gives an estimate of the illumination

# Reconstruction from CBP data (3)




5) Smooth *this* with a spline

Figure credit: R. Lupton

# Reconstruction from CBP data (4)

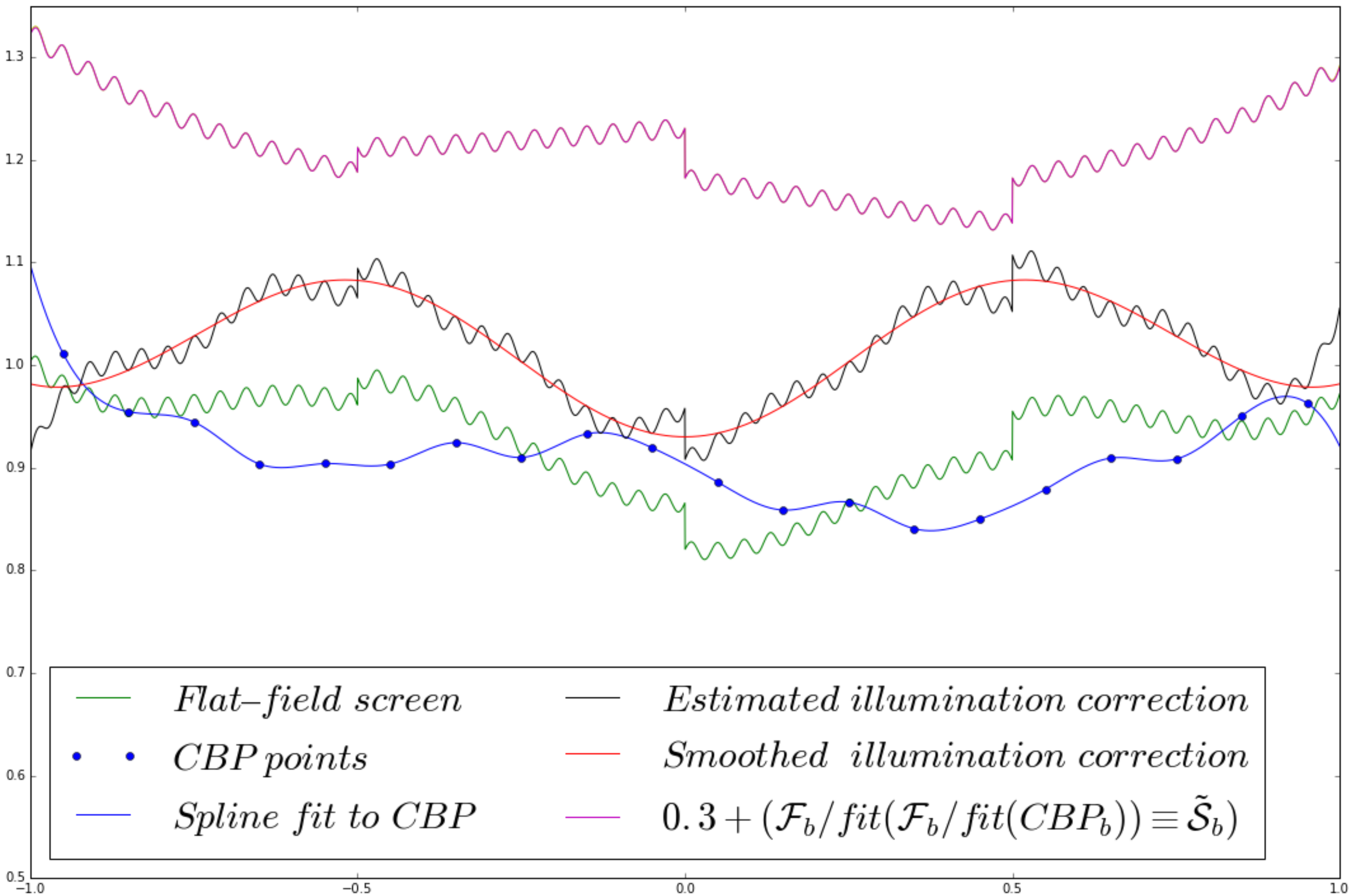



Figure credit: R. Lupton

6) Divide the flat-field by the smoothed illumination correction

# Residuals

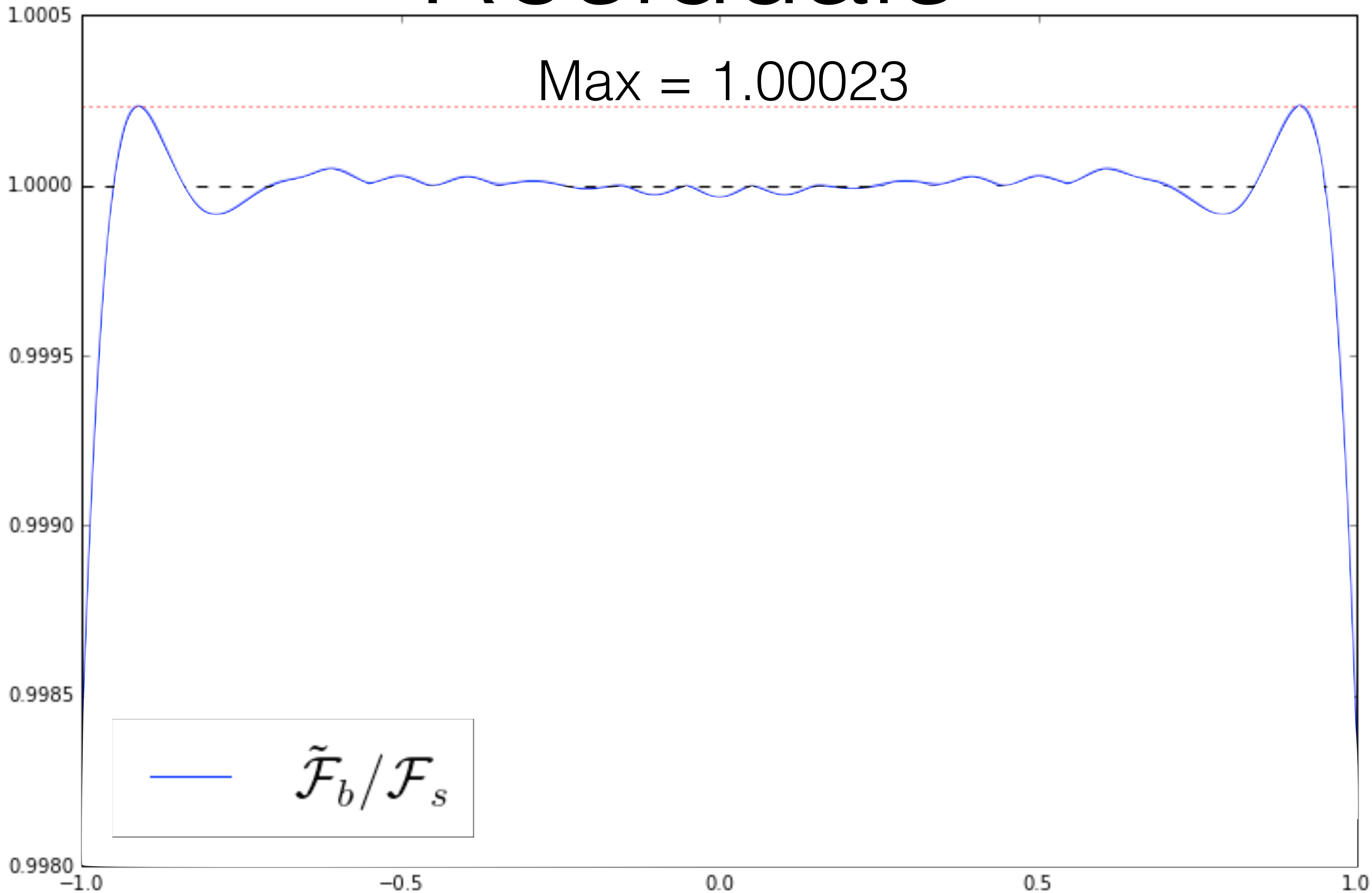



Figure credit: R. Lupton

# Reconstruction from CBP data (1)

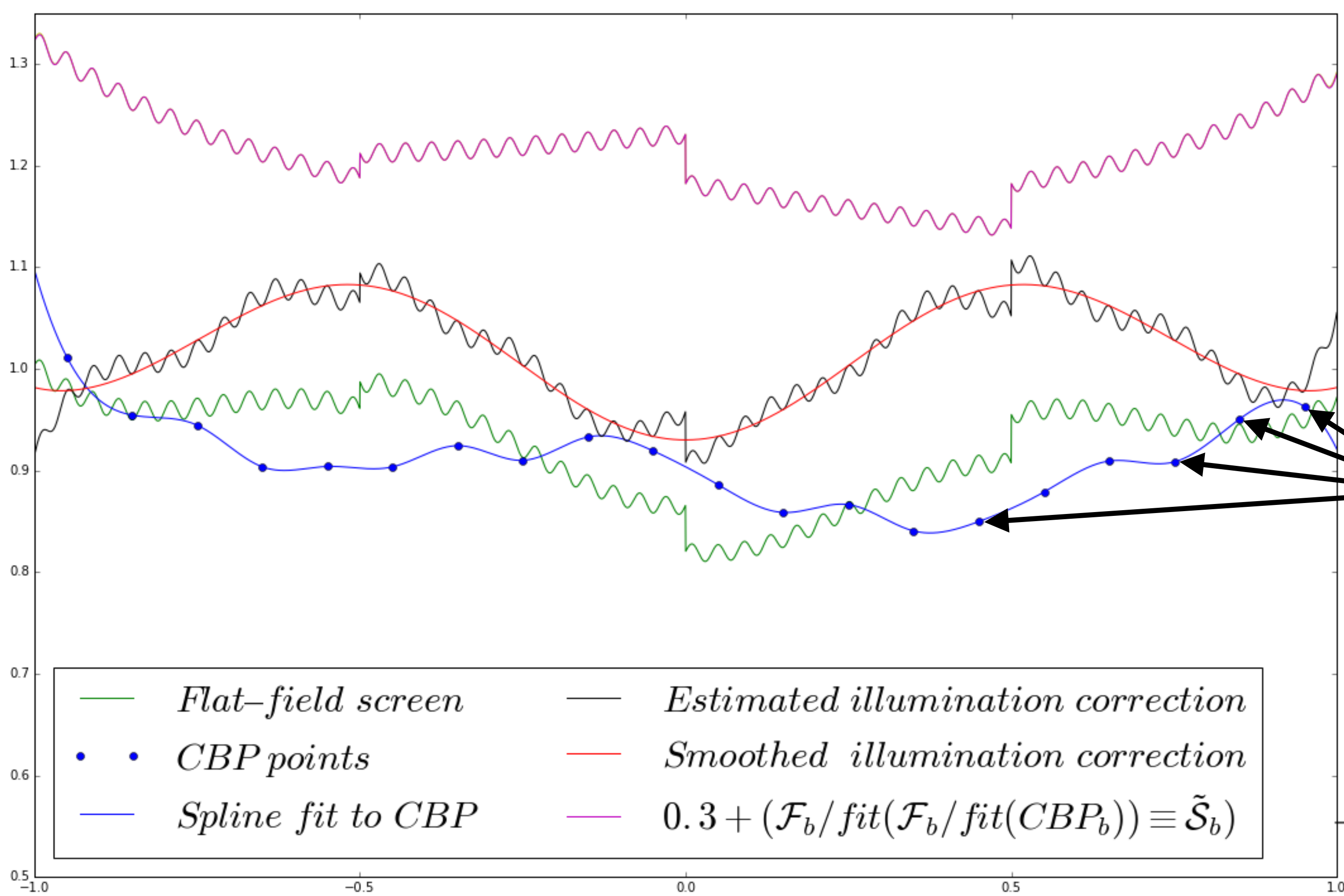
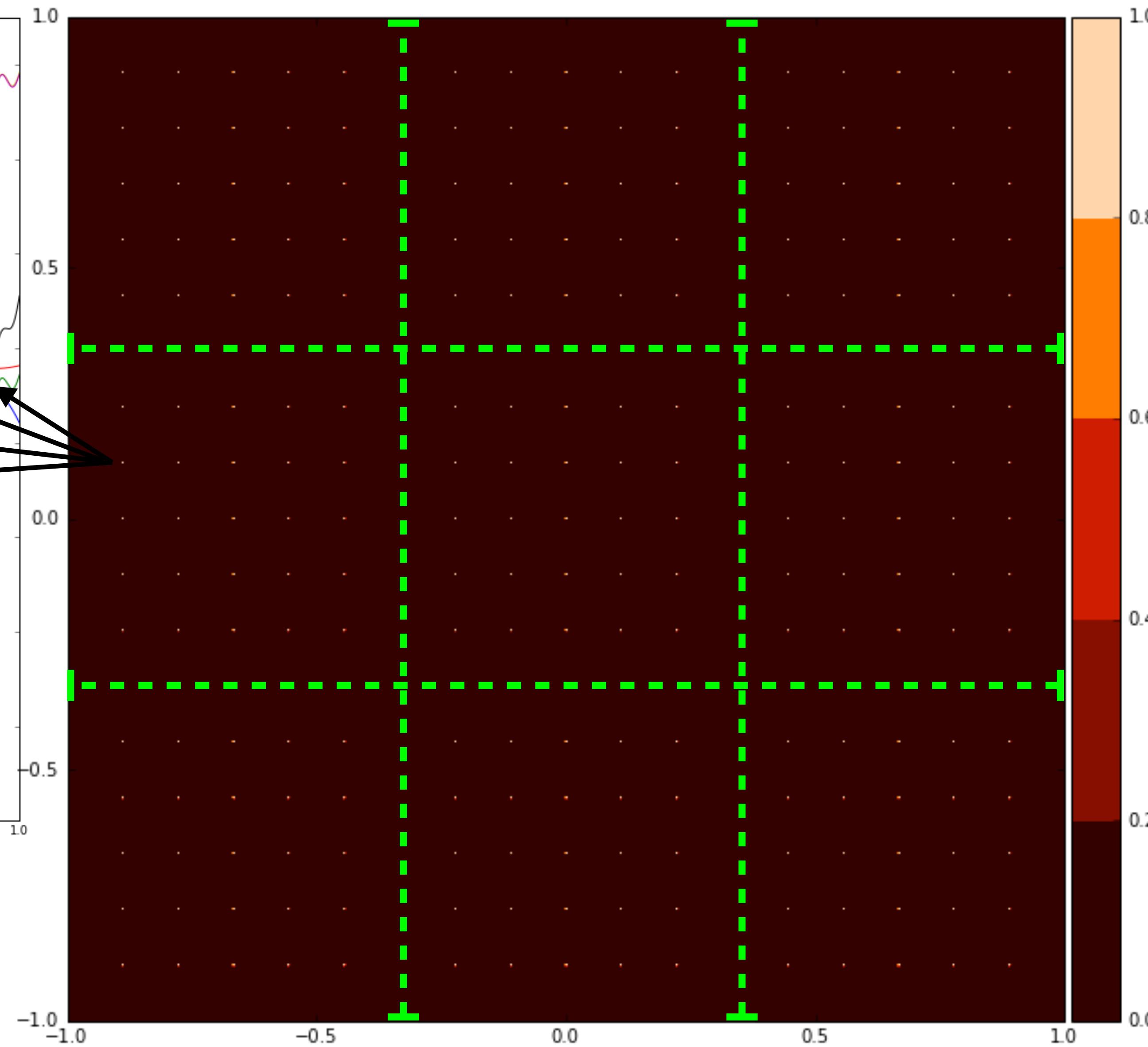



Figure credit: R. Lupton



Place sample points in 2D

1D

2D

# Reconstruction from CBP data (1)

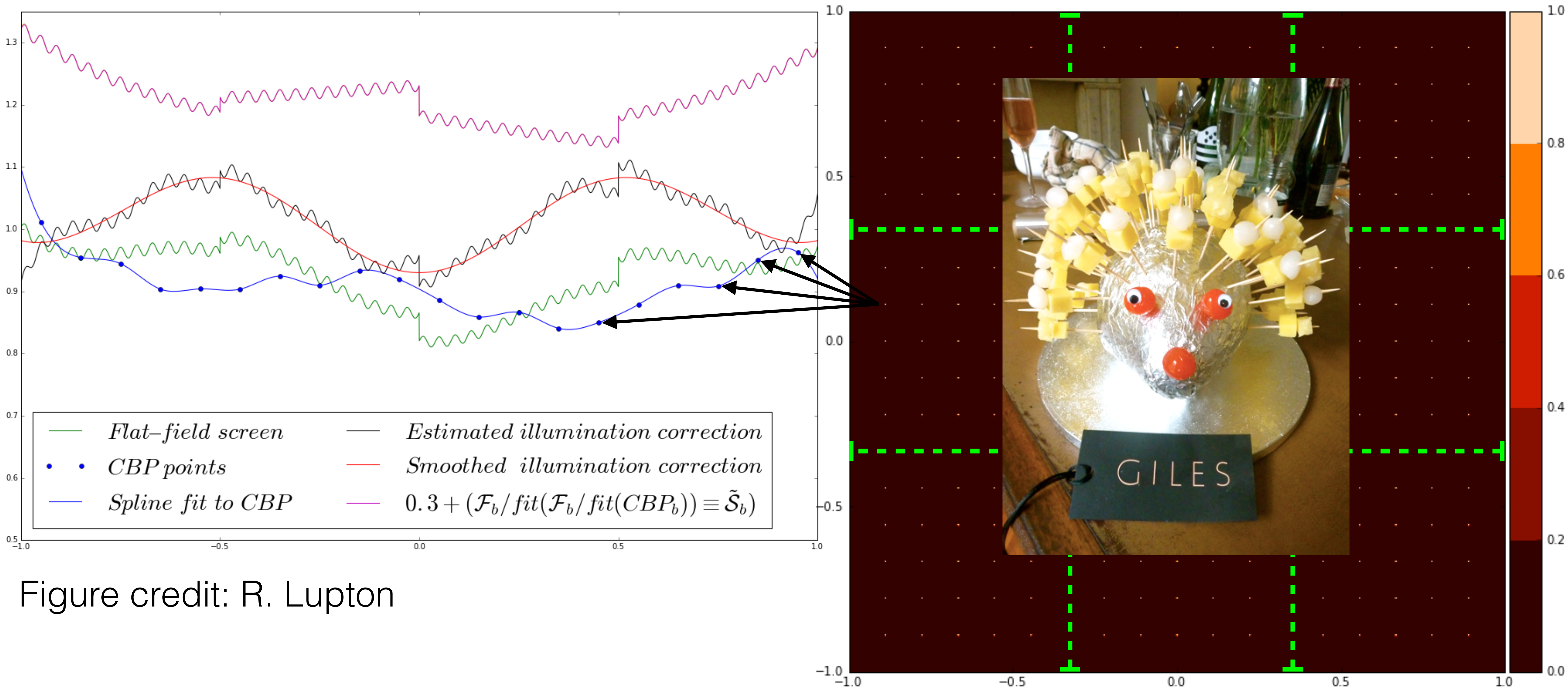



Figure credit: R. Lupton

Place sample points in 2D

1D

2D

# Reconstruction from CBP data (2)

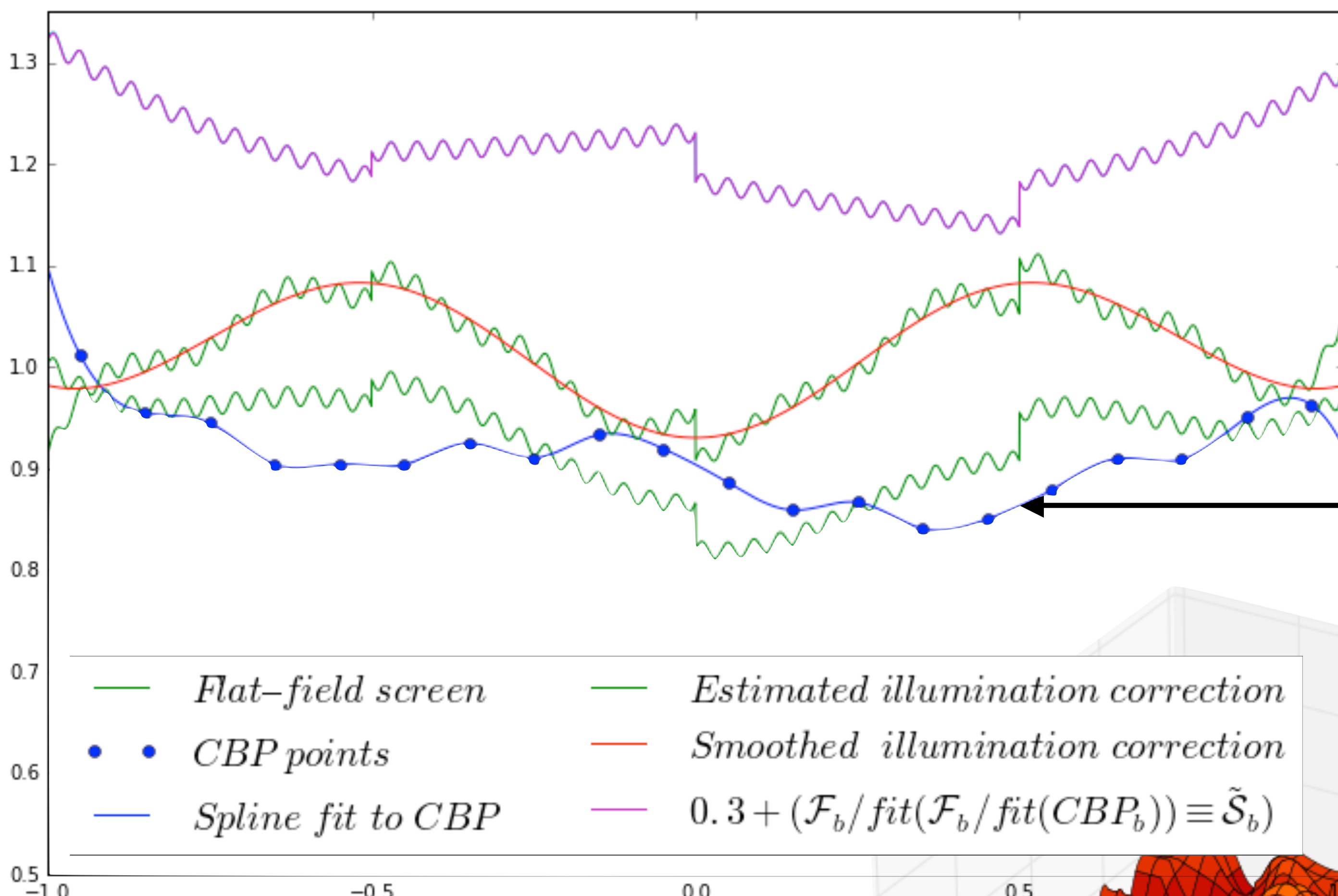
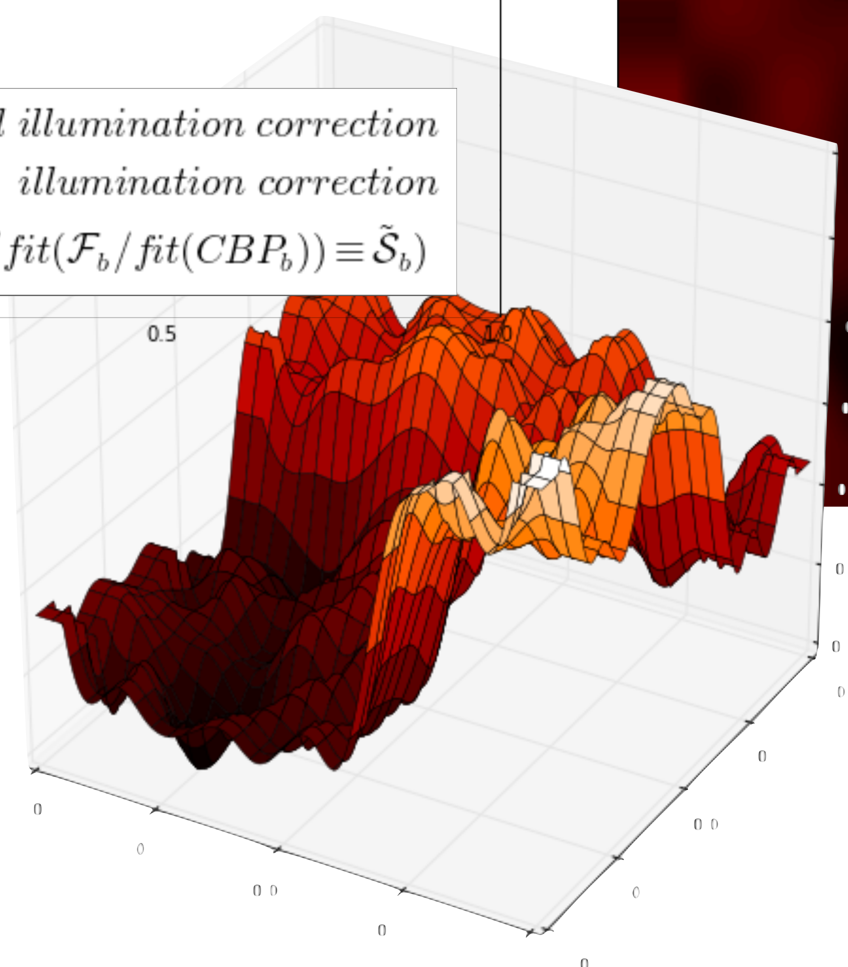
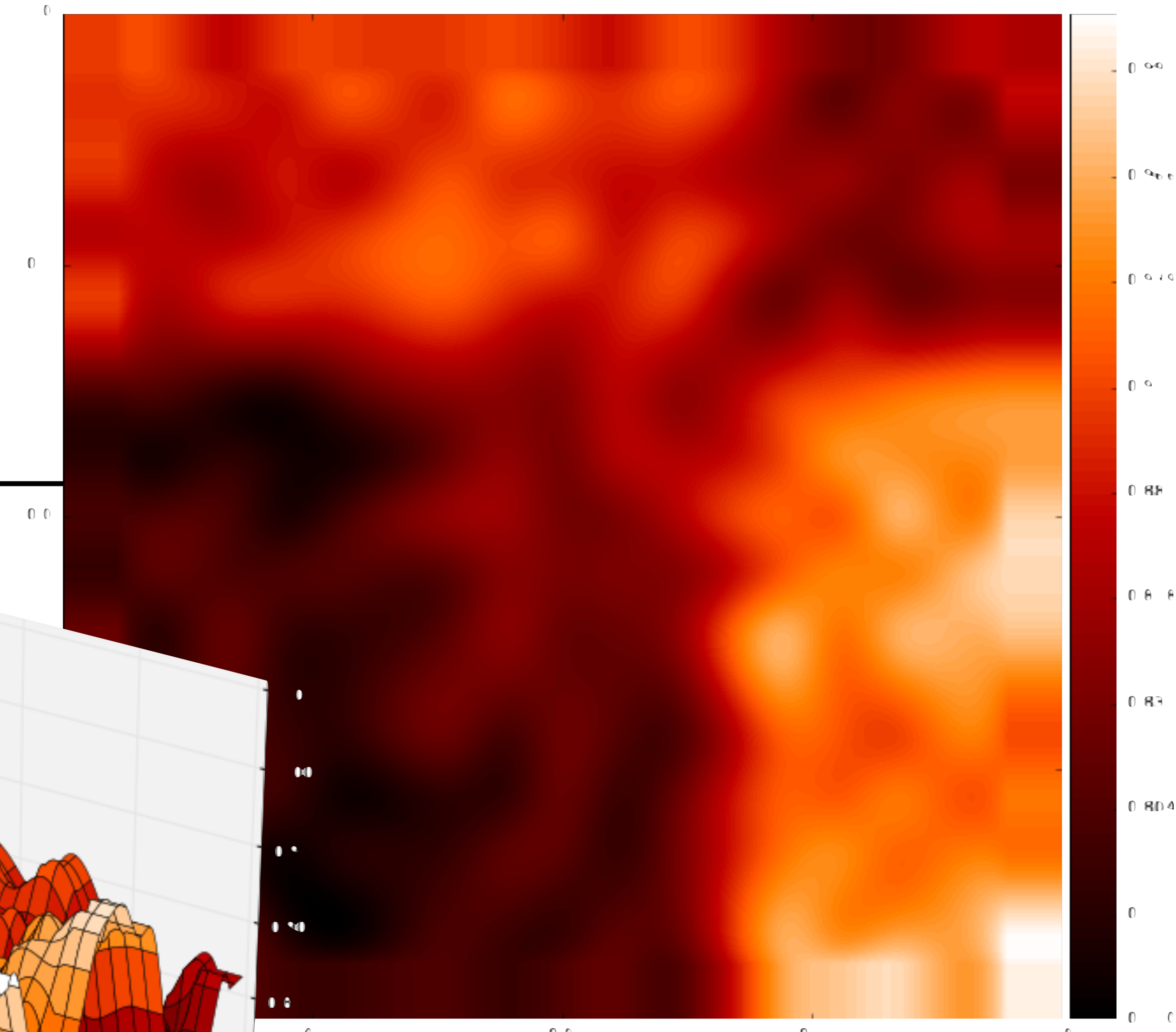



Figure credit: R. Lupton





Take data at sample points & interpolate

1D

2D

# Reconstruction from CBP data (3)

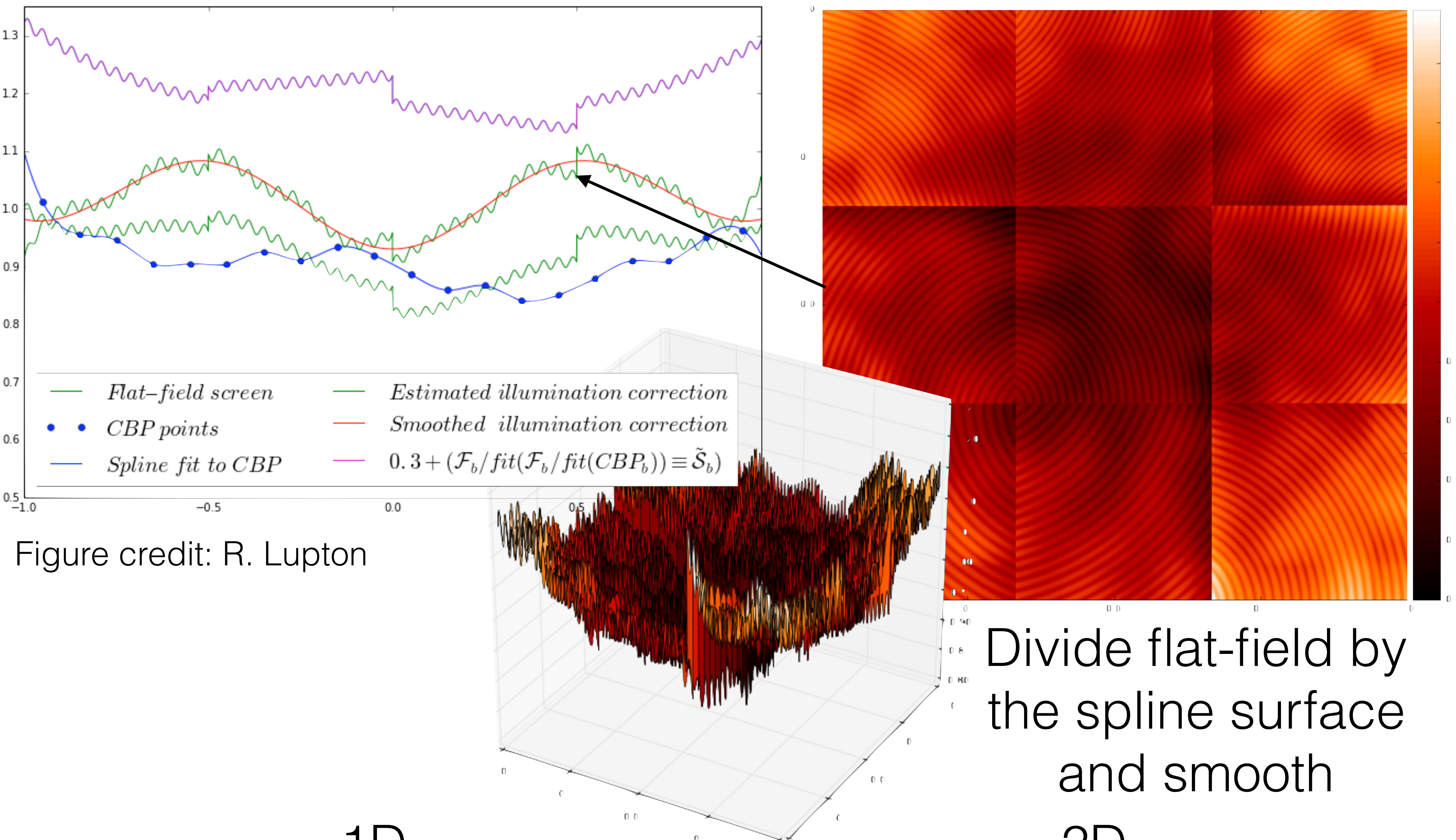



Figure credit: R. Lupton

Divide flat-field by the spline surface and smooth

1D

2D

# Reconstruction from CBP data (4)

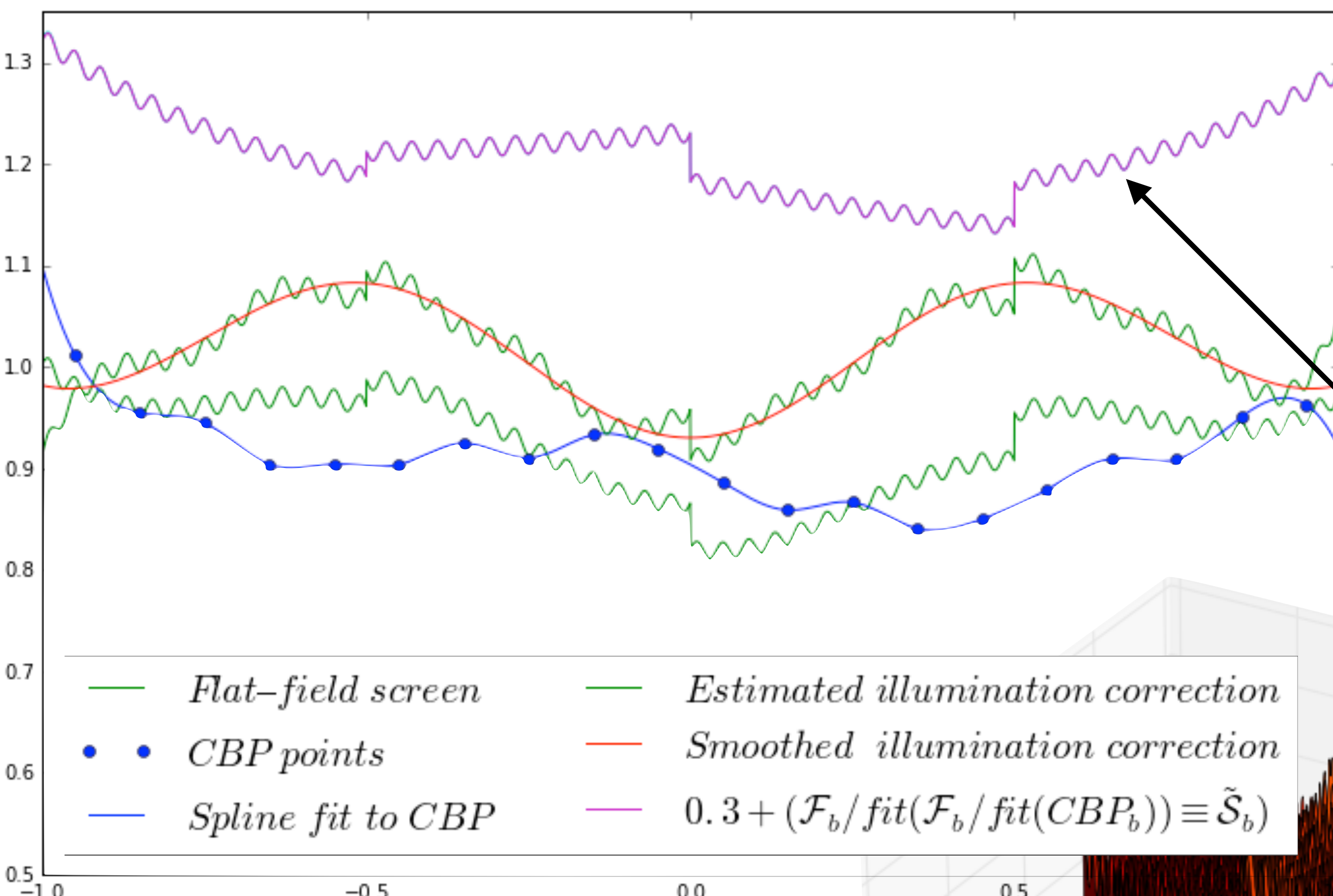
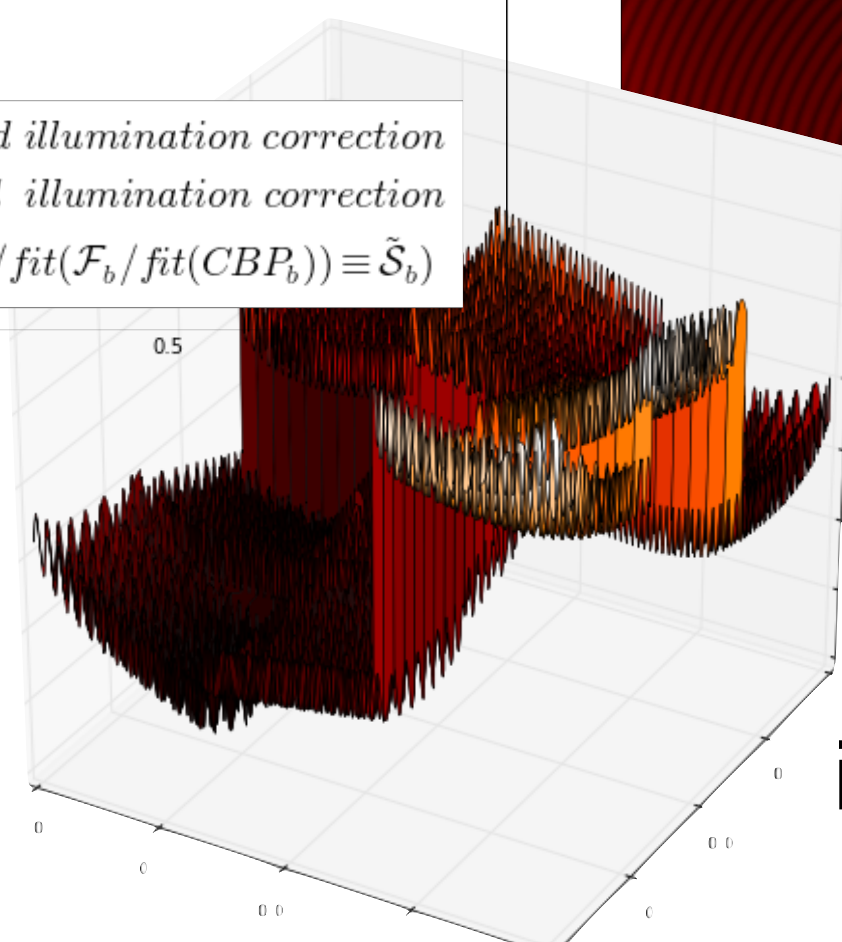
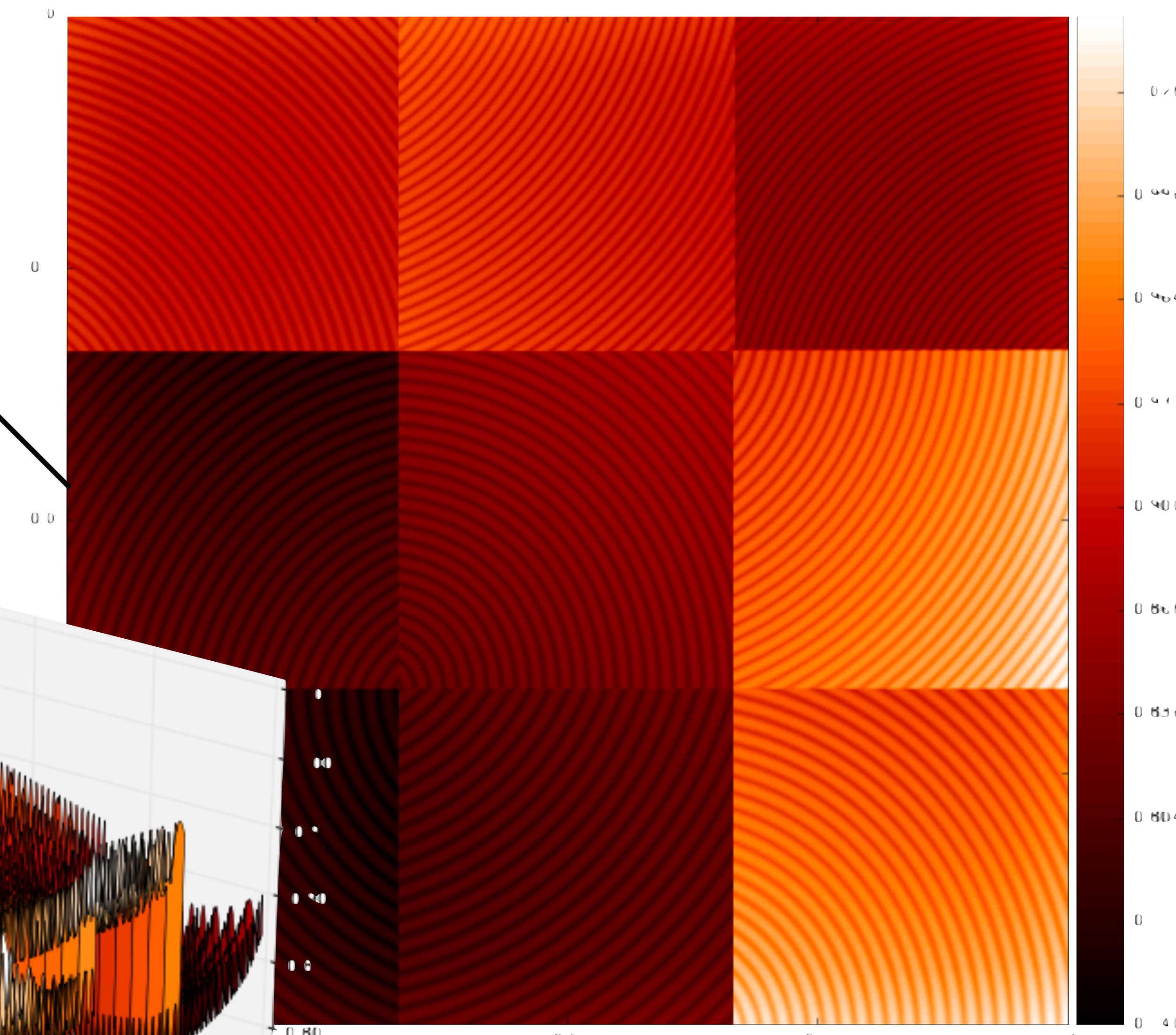



Figure credit: R. Lupton





Apply derived illumination correction

1D

2D

# Reconstruction from CBP data (5)

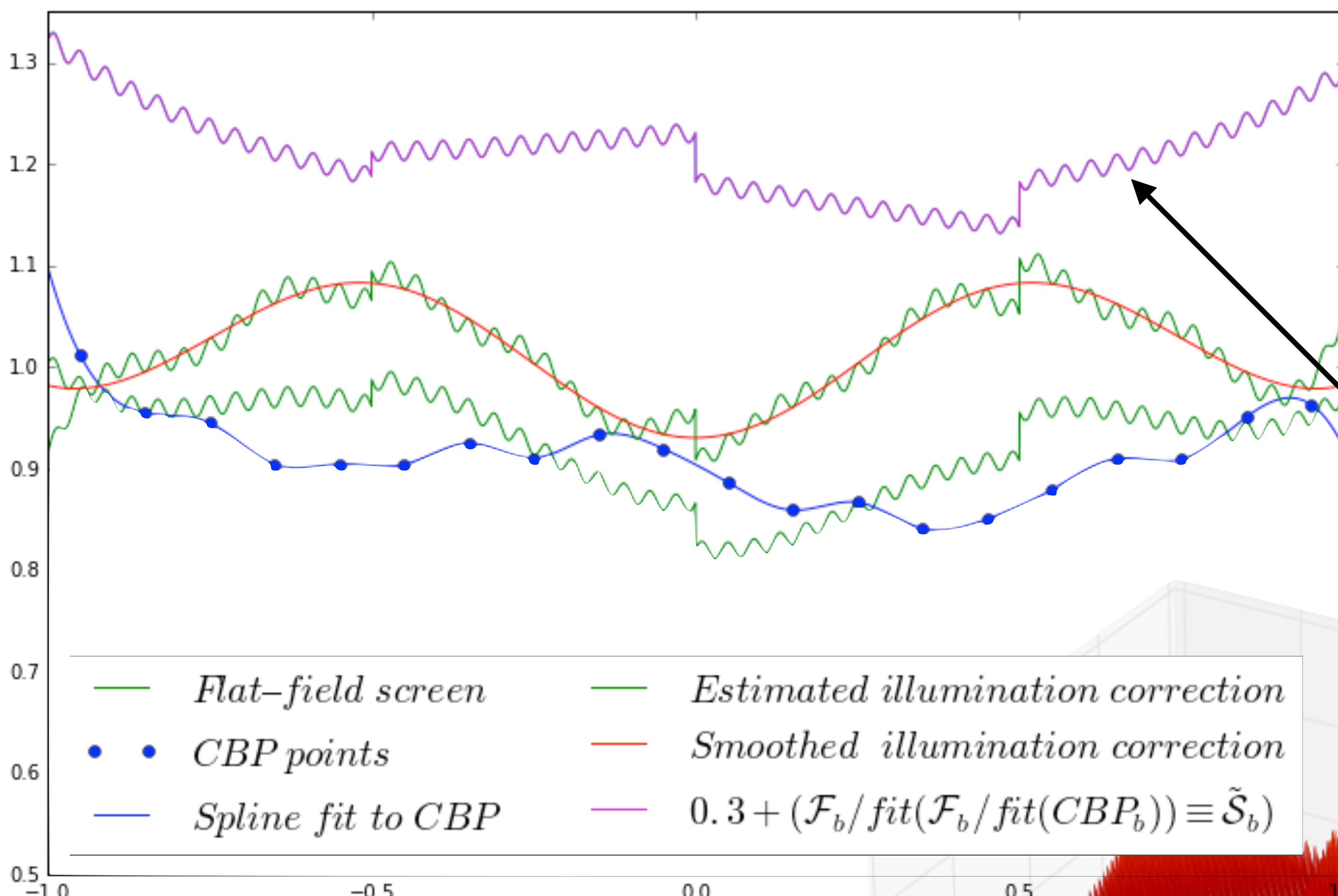
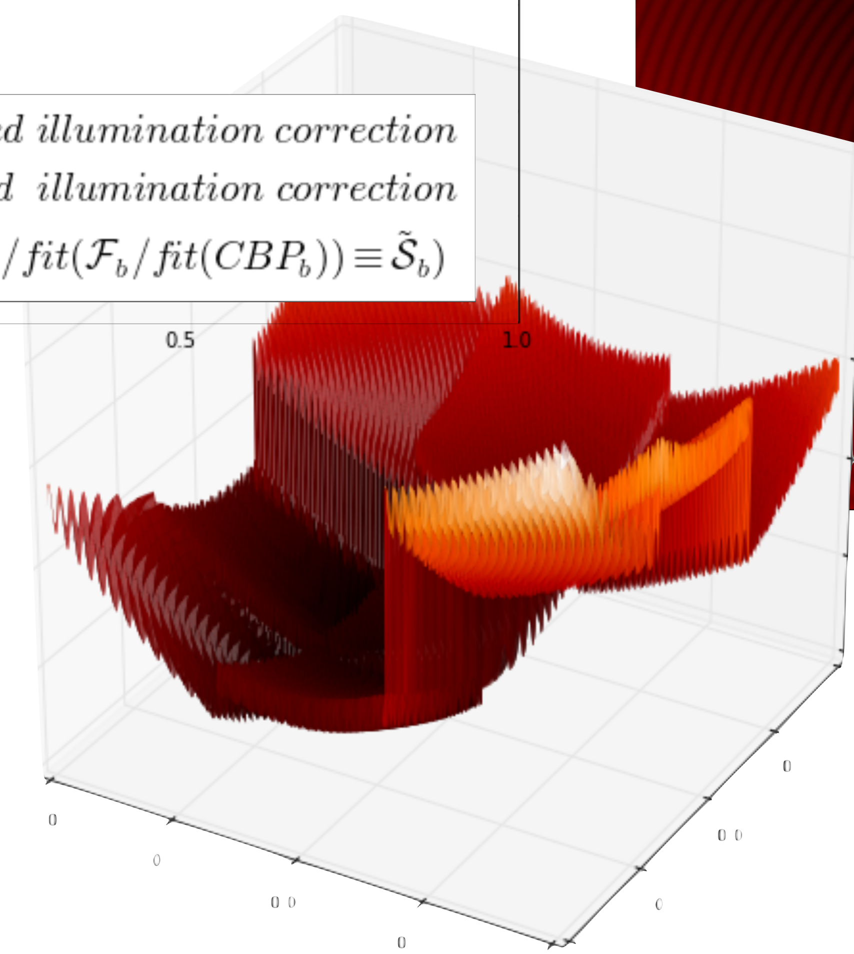
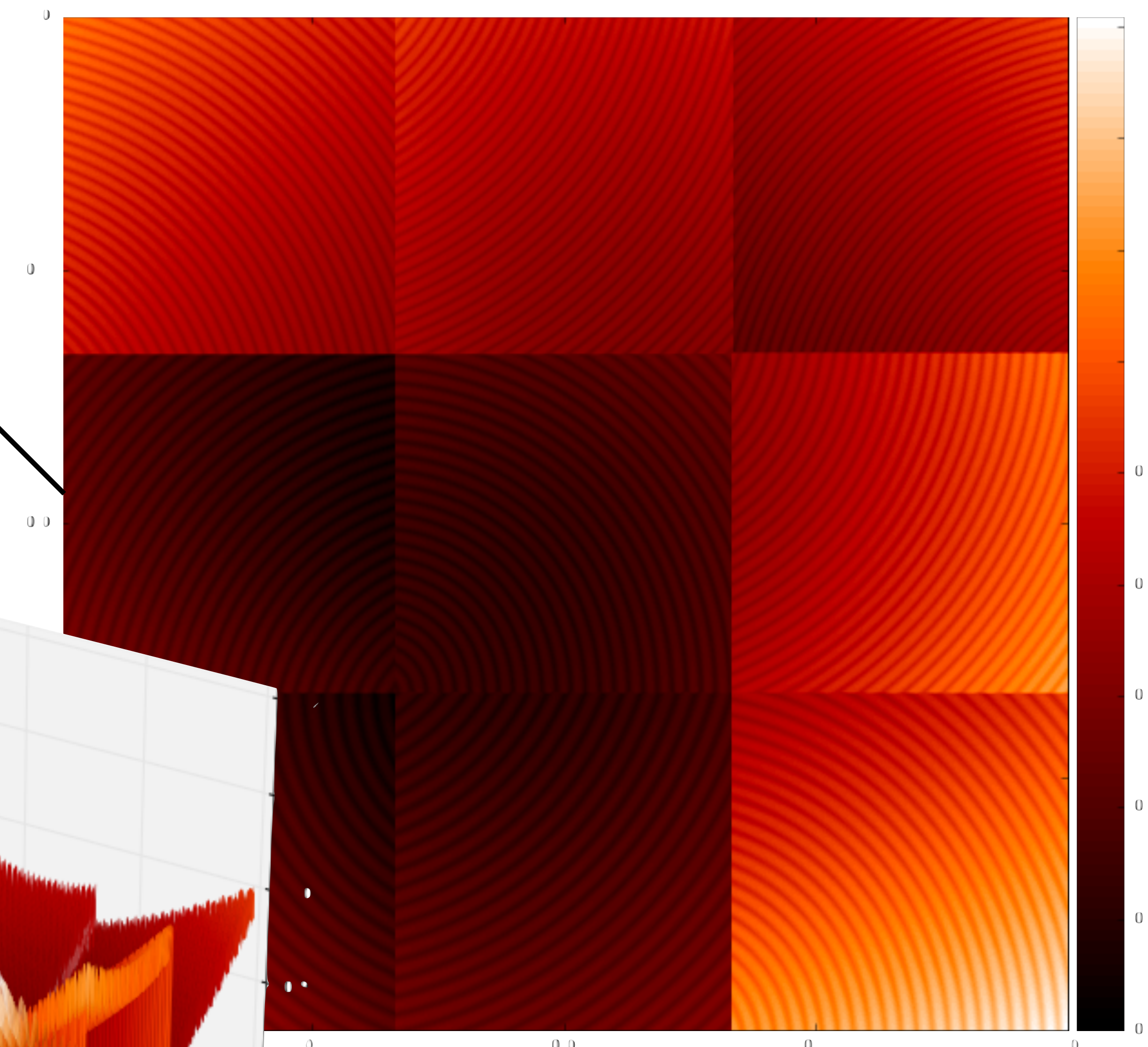



Figure credit: R. Lupton



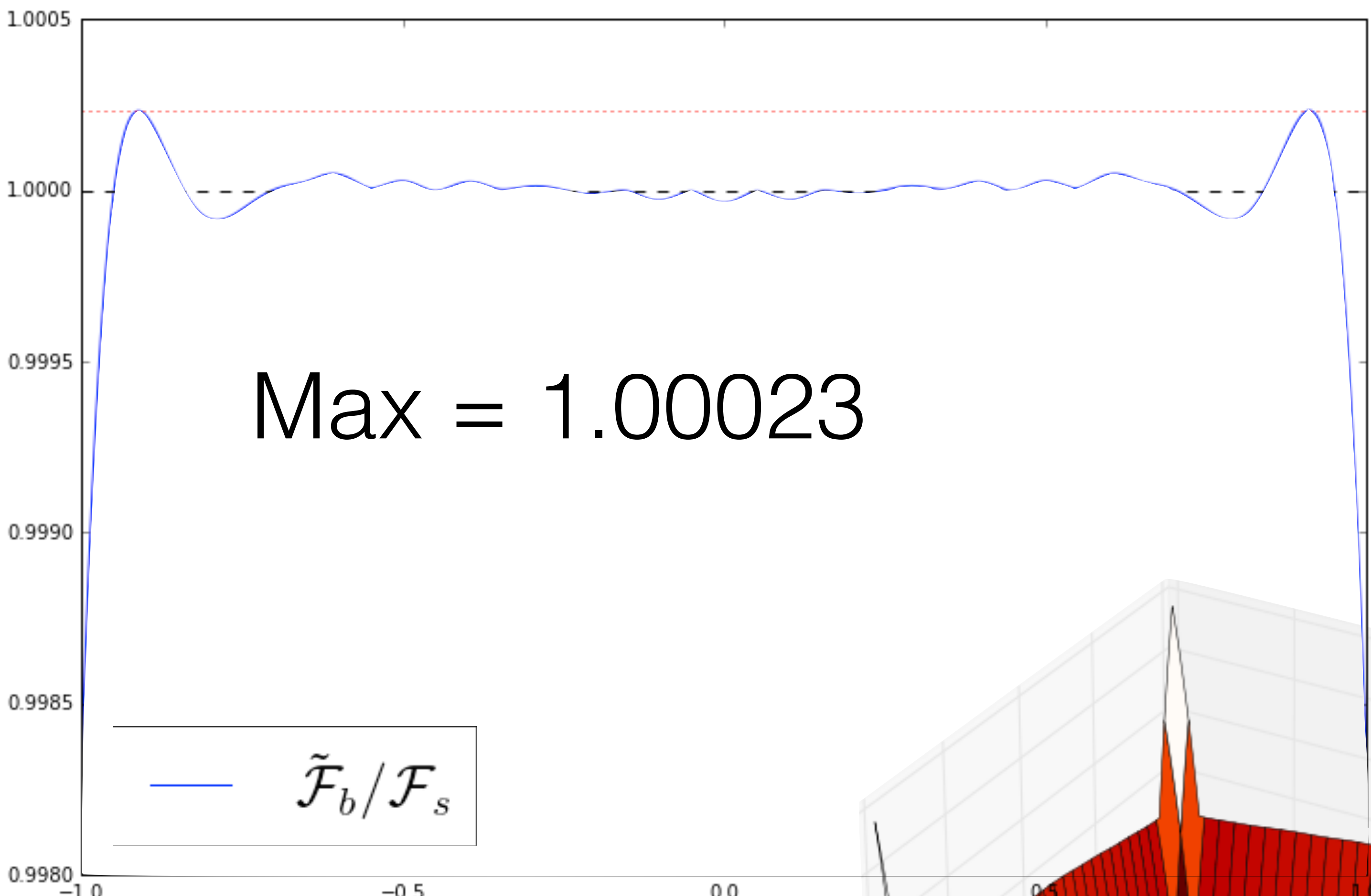


Arrive at system response, plot residuals…

1D

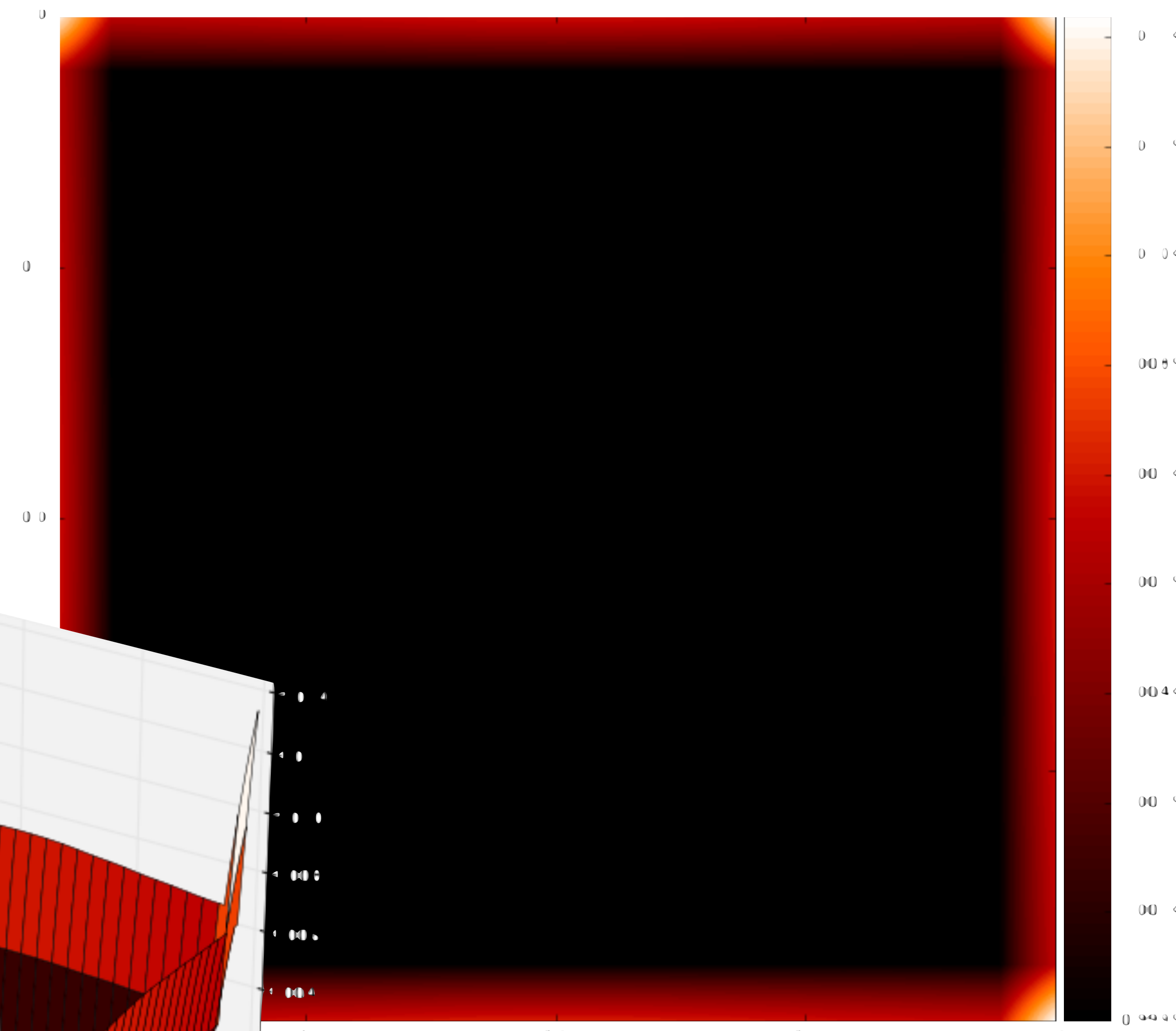
2D

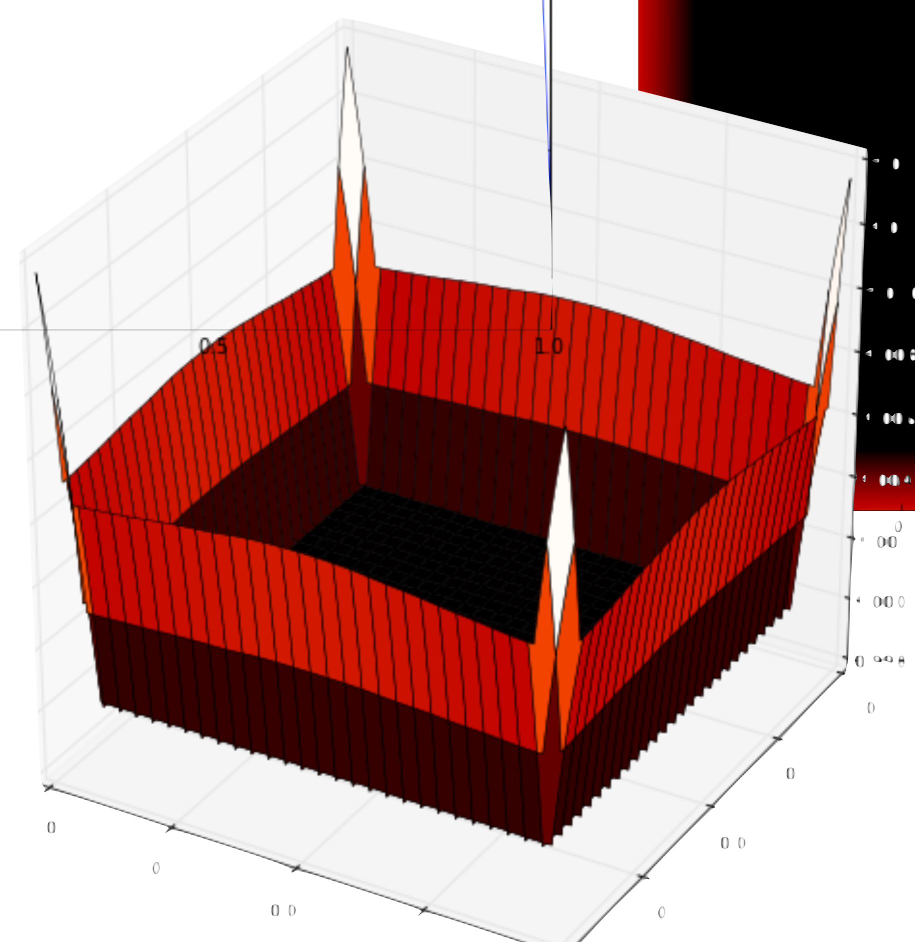
# Residuals




Max = 1.00023

Figure credit: R. Lupton



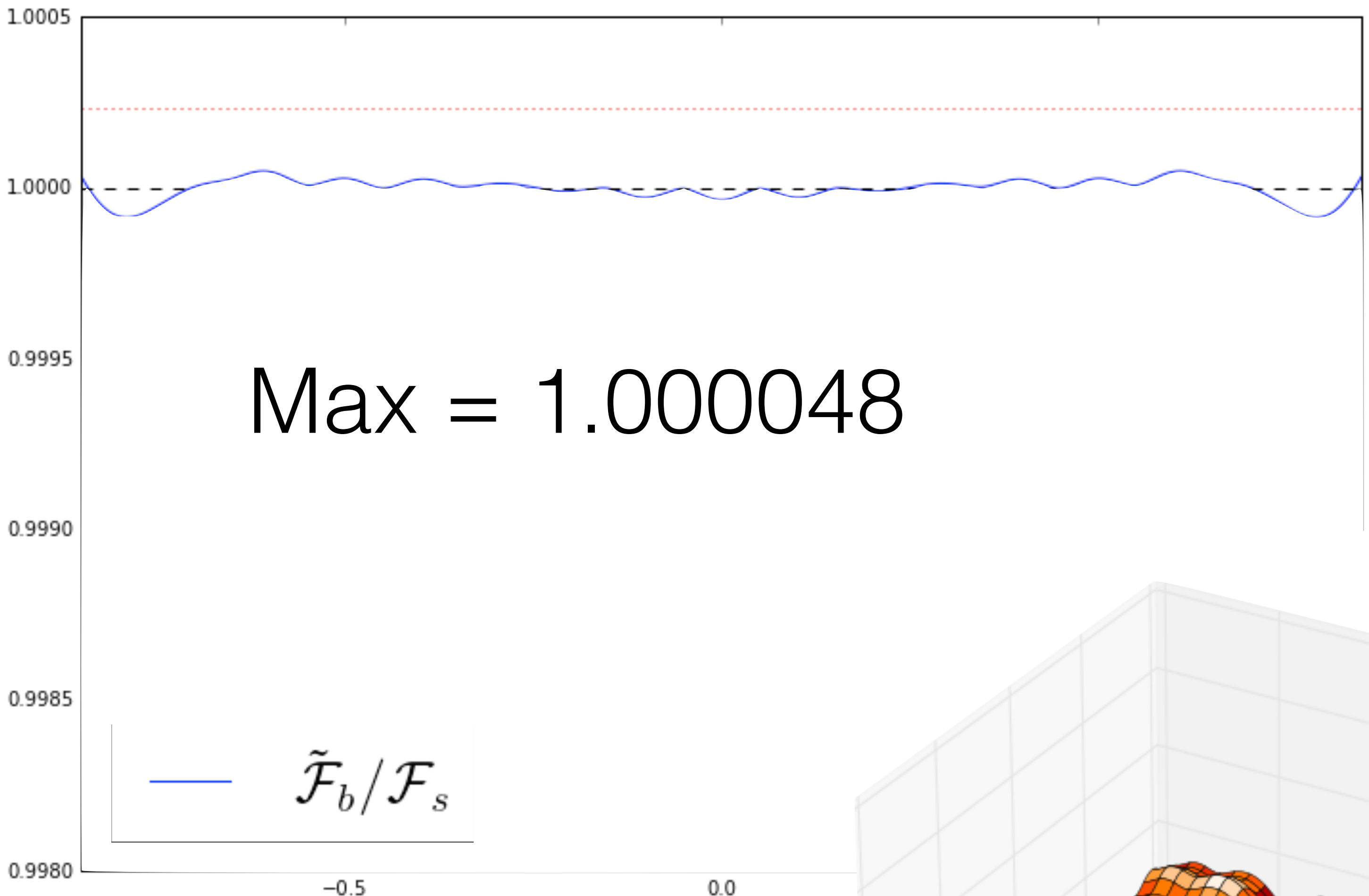


Max = 1.0137

1D

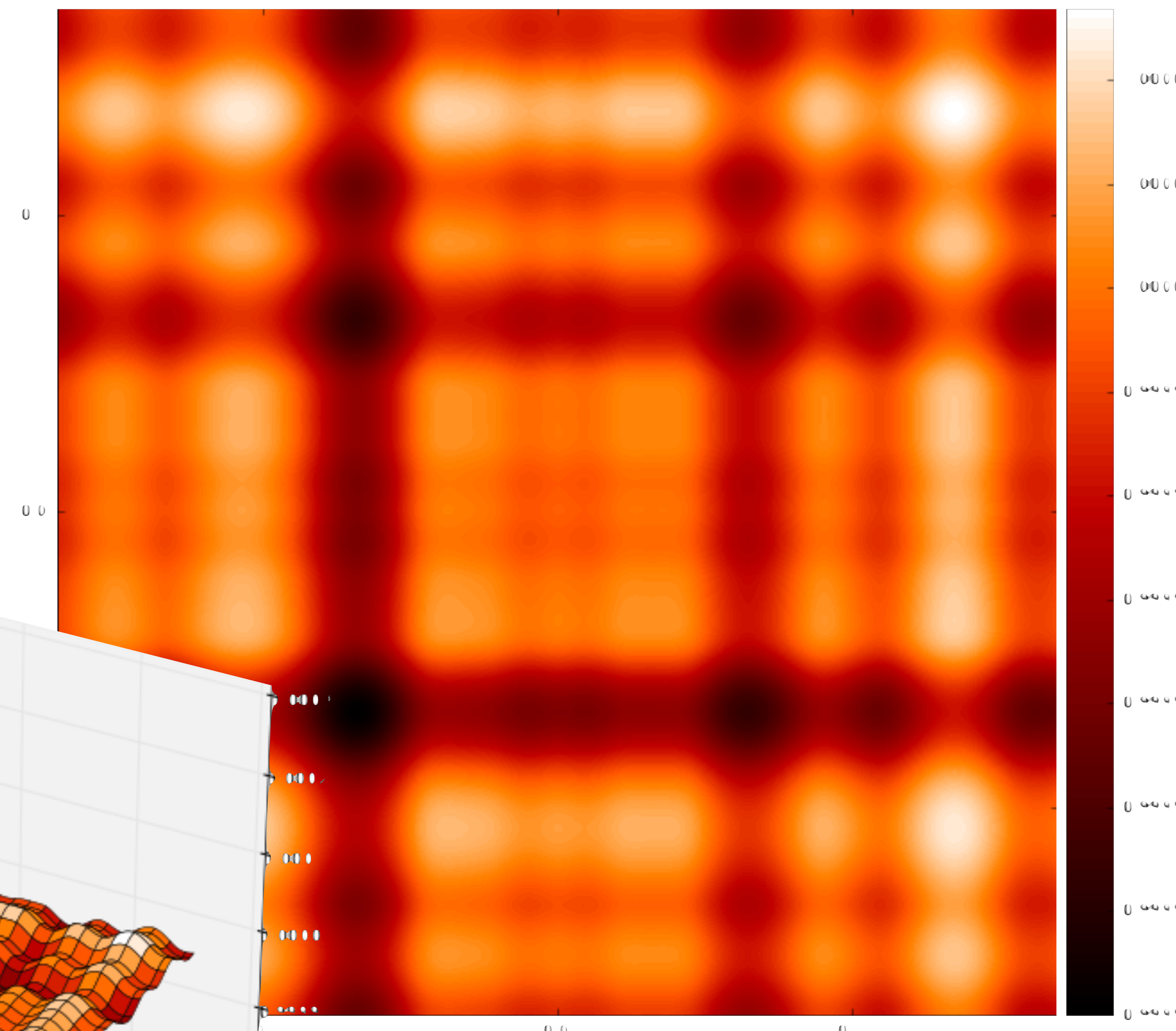
2D

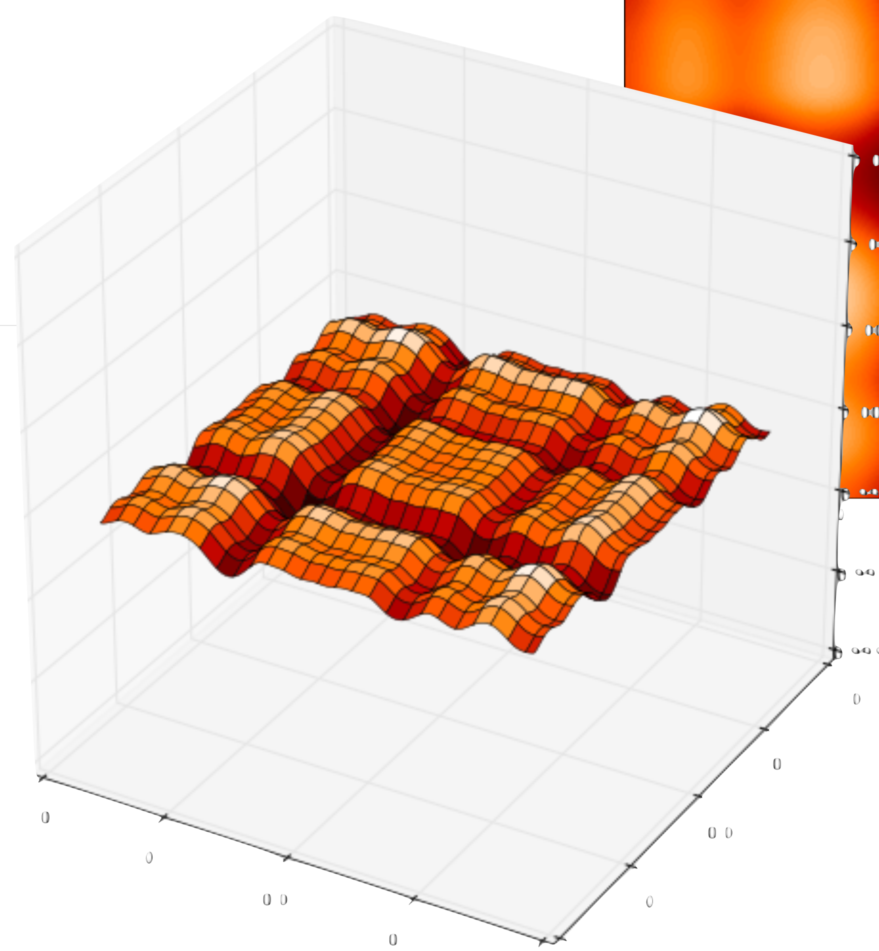
# Residuals




Max = 1.000048

Figure credit: R. Lupton





Max = 1.000021

1D

2D

# It's real!

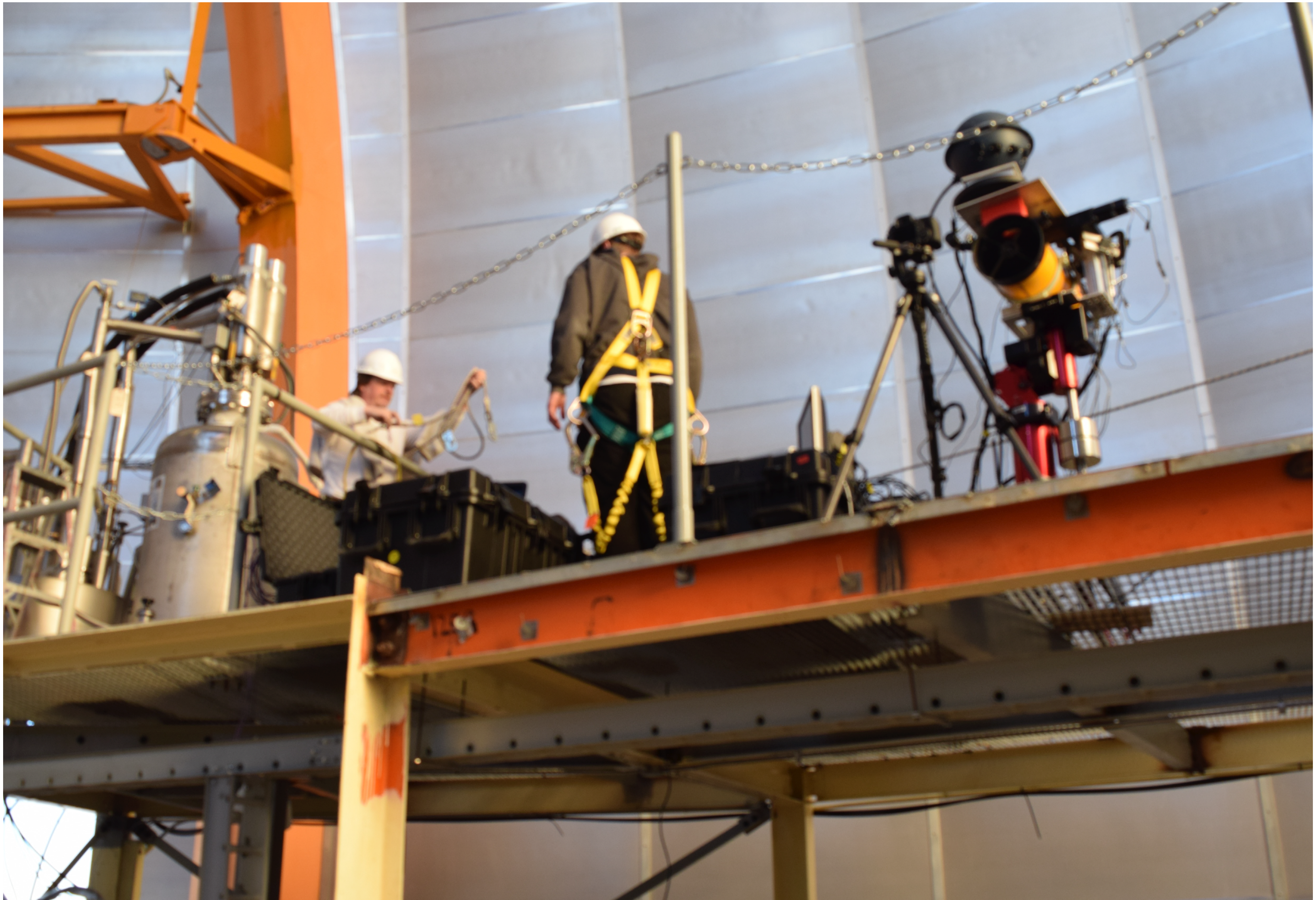
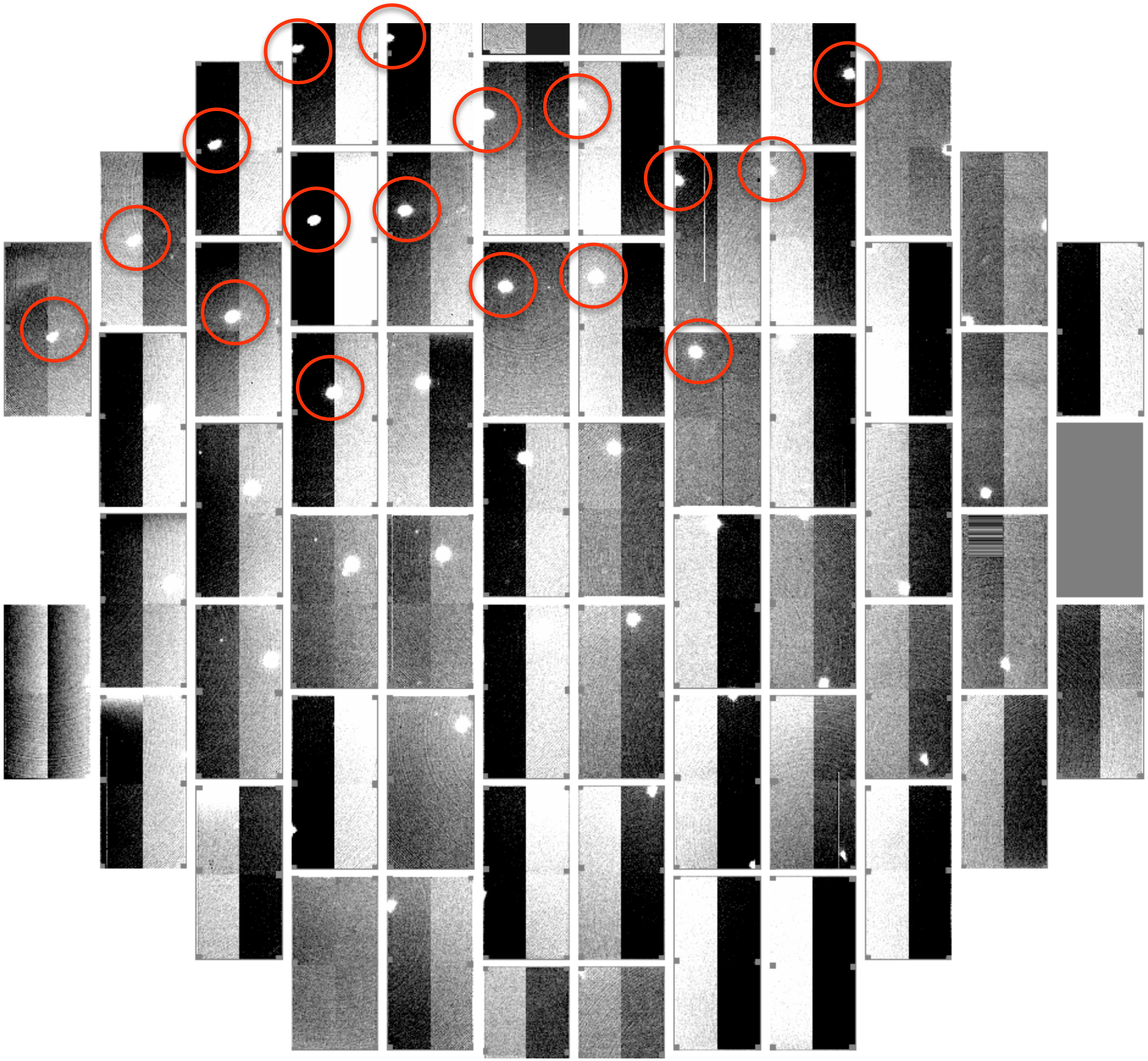


Photo credit: M. Coughlin

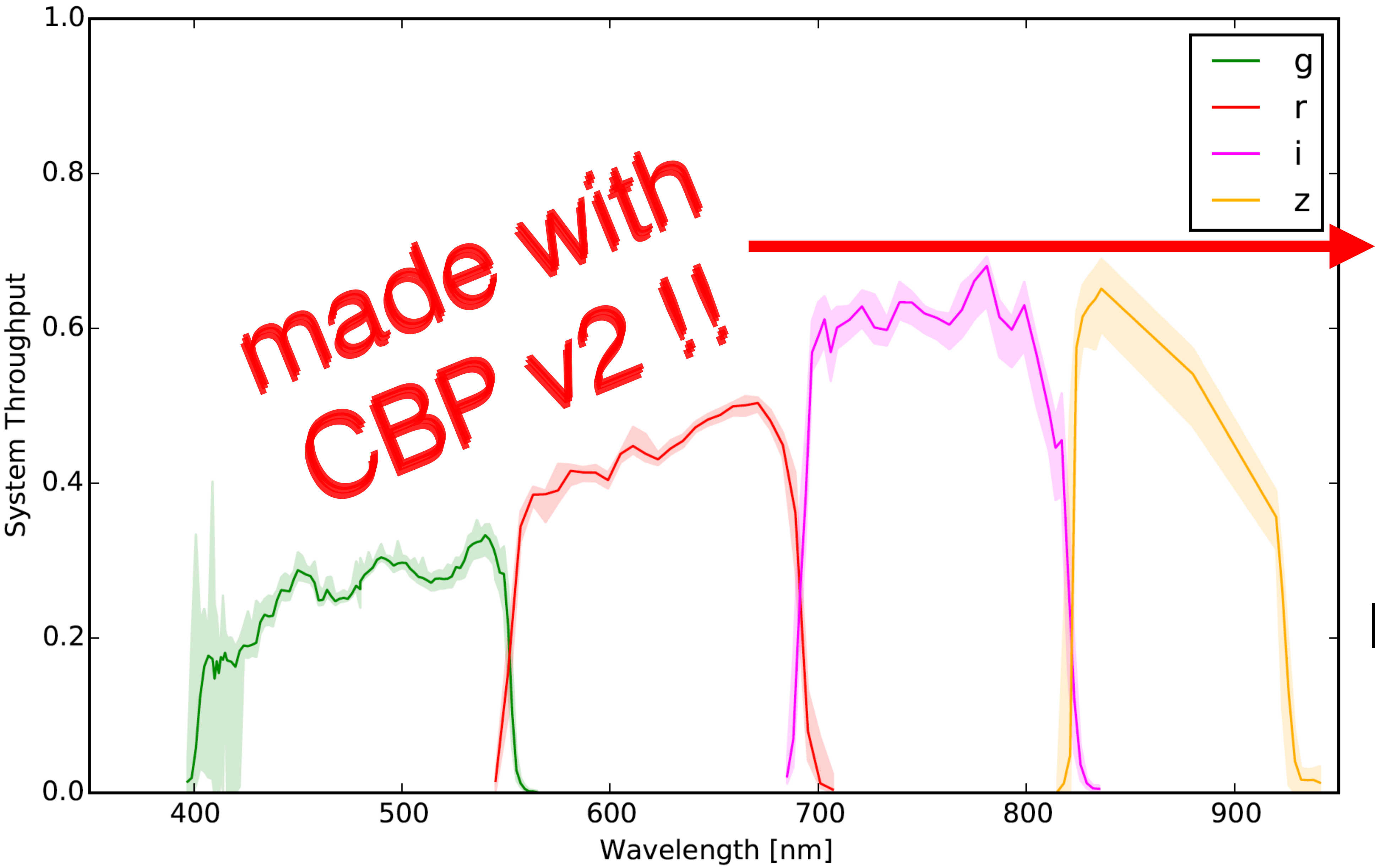
# It works! (At CTIO/DECam)



- 1st prototype
- Focus was poor due to rough transit
- For a first try it worked wonderfully!

# It works! (At Pan-STARRS)

Filter transmission measurement at Pan-STARRS



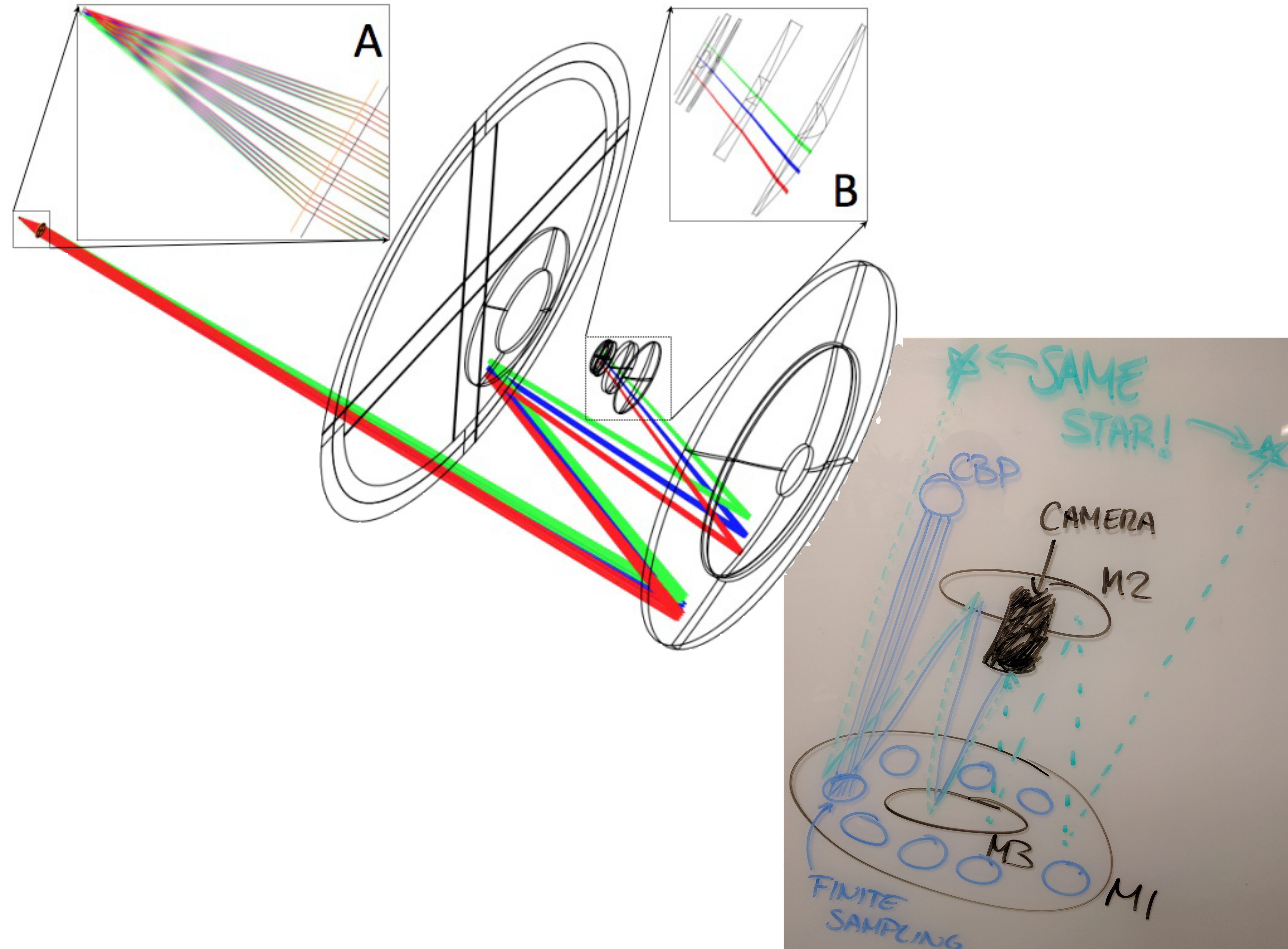

CBP v2:
New and improved!
Now with
smaller spots!

Figure credit: M. Coughlin, N. Mondrik, J. Tonry, C. Stubbs

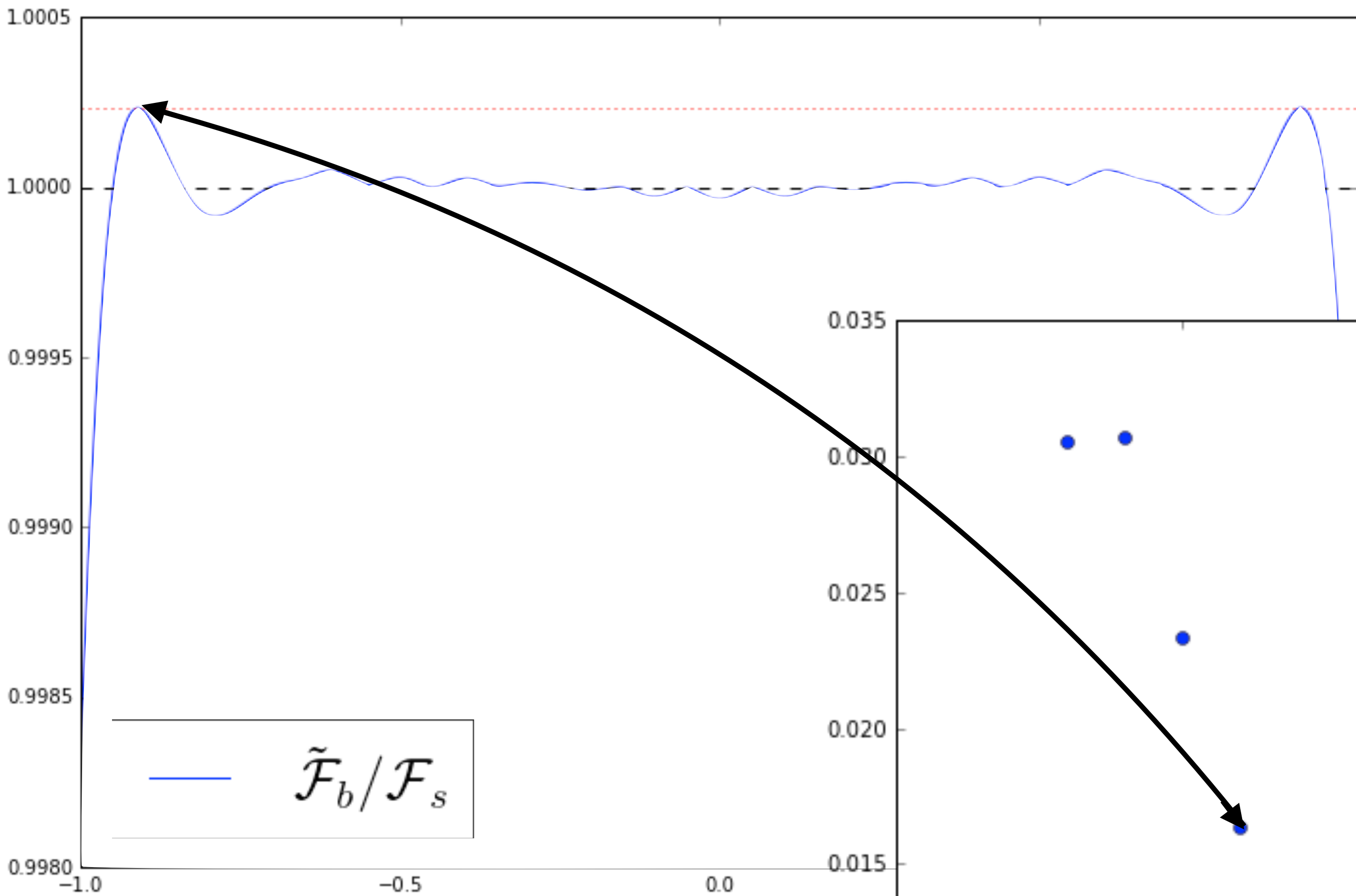
# Conclusion

- The CBP allows us to:
  - Calculate the system response function, $\boldsymbol{S_{sys}}$, and correct for the ghosting and non-uniform illumination in dome-flats
  - Do this as a function of wavelength by using monochromatic light for both dome-flats and CBP illumination
  - Thereby accurately flat-field our images to unprecedented precision, and do so correctly for any given SED
  - Sample only a portion of the pupil at a time, allowing characterisation of the filter transmission as a function of position
- As a bonus, we also get help with crosstalk measurements and monitoring the evolution of the filter bandpasses over time.

# Backup slides


A
B
SAME STAR!
CBP
CAMERA
M2
M3
M1
FINITE SAMPLING

# Residuals vs. CBP samples




How does the error change with number of number of CBP samples taken per chip?